

**BUILDINGS, BEAUTY, AND THE BRAIN:**  
**PSYCHOLOGICAL RESPONSES TO ARCHITECTURAL DESIGN**

ALEXANDER CRONE COBURN

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68,644 WORDS

## **Author's Declaration**

This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration except as declared in the Preface and specified in the text. It is not substantially the same as any that I have submitted, or, is being concurrently submitted for a degree or diploma or other qualification at the University of Cambridge or any other University or similar institution except as declared in the Preface and specified in the text. I further state that no substantial part of my dissertation has already been submitted, or, is being concurrently submitted for any such degree, diploma or other qualification at the University of Cambridge or any other University or similar institution except as declared in the Preface and specified in the text. It does not exceed the prescribed word limit for the relevant Degree Committee.



## Abstract

*Title: Buildings, beauty, and the brain: psychological responses to architectural design*

*Author: Alexander Crone Coburn*

People today spend most of their lives in buildings. The design of the built environment can impact mood, behavior, and wellbeing. The evidence discussed in Chapter 1 suggests that the perceived *beauty* of an environment may influence wellbeing more than any single design variable considered in isolation. Some researchers have leveraged empirical methods of neuroscience and psychology to identify aesthetic features of architecture that support healthy psychological experiences. However, this line of inquiry faces persistent challenges in terms of a) measuring the environment itself and b) evaluating acute psychological responses relevant to design. This dissertation addresses both of these gaps in the literature by using pattern theory and image statistics to quantify aesthetic properties of architectural scenes (Chapters 4-5), and by advancing our understanding of how specific neural networks and psychological processes contribute to architectural experience (Chapters 2-3).

Chapter 2 outlines the first neuroscientific model of architectural encounters. According to this *aesthetic triad* framework, three large-scale neural systems generate aesthetic experiences in the built environment: sensorimotor, emotion-valuation, and knowledge-meaning systems. The chapter explores how design features interact with each of these neural systems to influence mental states and behaviors and investigates how emerging technologies like virtual reality and brain imaging could be leveraged in future research on the neuroscience of architecture. Building from this neural model, Chapter 3 investigates the core psychological dimensions of architectural experience within the context of the *aesthetic triad* framework. In a pair of experiments, participants rated architectural images on a series of diverse psychological measures. A Principal Components Analysis yielded three components that explained most of the variance in ratings: *fluency* (ease with which one organizes and comprehends a scene), *fascination* (a scene's informational richness and generated interest), and *hygge* (extent to which the scene reflects a warm, personal

environment).<sup>1</sup> Whereas *fluency* and *fascination* are well-established dimensions in assessing natural scenes and visual art, *hygge* emerged as a new dimension in relation to architectural scenes.

In Chapters 4 and 5, the focus shifts from measuring the brain to measuring the environment. Specifically, these chapters investigate whether people are innately attuned to nature-like visual patterns in architecture. Chapter 4 introduces Christopher Alexander's theory of *natural structure* and reviews past literature linking biophilic design and wellbeing. In Chapter 5, a series of experiments are presented suggesting that subjective perceptions of naturalness are strongly predicted by low-level visual features of architectural scenes. Furthermore, naturalistic scaling and contrast features – two of Alexander's proposed patterns of *natural structure* – are found to reliably predict similarity evaluations (derived from an image arrangement task) and aesthetic preference ratings of architectural scenes. The results of a final experiment suggest that preferences for nature-like architectural patterns may be associated with feelings of comfort and excitement that such patterns generate.

This research adds to a growing body of literature showing how aesthetic qualities of architecture impact human experiences. Novel theoretical frameworks are proposed for researchers to contextualize empirical studies on the psychology and neuroscience of architecture. New methods of image analysis are also used to quantify aesthetic properties of the built environment and to investigate how nature-like patterns in architecture influence psychological experiences. Together, these chapters provide new insight into the psychological influence of our physical surroundings, and they offer new research tools to inform the design of beautiful and brain-friendly buildings.

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<sup>1</sup> *Hygge* is a Danish word that describes “a feeling of coziness, warmth, and togetherness” (Wiking, 2017, p. 25) that is often felt in the presence of intimate spaces and social settings. This concept is further explained in the “discussion” section of Chapter 3.

# Table of Contents

AUTHOR'S DECLARATION .....	I
ABSTRACT .....	II
TABLE OF CONTENTS .....	IV
FIGURES.....	VII
TABLES .....	X
ACKNOWLEDGEMENTS .....	XII
COLLABORATIONS .....	XIII
DISSEMINATION OF THIS RESEARCH .....	XVIII
PERSONAL JOURNEY .....	XIX
<b>GENERAL INTRODUCTION .....</b>	<b>1</b>
SUMMARY OF RESEARCH .....	1
ENVIRONMENTAL BEAUTY AND WELLBEING.....	1
A NEUROSCIENTIFIC MODEL OF ARCHITECTURAL EXPERIENCE .....	2
PSYCHOLOGICAL RESPONSES TO ARCHITECTURAL INTERIORS .....	2
NATURAL PATTERNS IN ARCHITECTURE.....	3
PSYCHOLOGICAL RESPONSES TO NATURAL PATTERNS IN ARCHITECTURE .....	4
SUMMARY AND CONCLUSIONS .....	5
<b>CHAPTER 1: ENVIRONMENTAL BEAUTY AND WELLBEING .....</b>	<b>6</b>
INTRODUCTION.....	6
THE EMERGING SCIENCE OF WELLBEING .....	6
WELLBEING AND THE BUILT ENVIRONMENT.....	14
CONCLUSION .....	26
<b>CHAPTER 2: A NEUROSCIENTIFIC MODEL OF ARCHITECTURAL EXPERIENCE .....</b>	<b>27</b>

INTRODUCTION.....	27
THE AESTHETIC TRIAD: A NEURAL MODEL OF ARCHITECTURAL EXPERIENCE .....	30
AUTOMATIC VS. NON-AUTOMATIC PROCESSING.....	41
NATURE VS. NURTURE.....	43
CHALLENGES & FUTURE DIRECTIONS .....	44
CONCLUSION .....	47
<b>CHAPTER 3: PSYCHOLOGICAL RESPONSES TO ARCHITECTURAL INTERIORS .....</b>	<b>48</b>
INTRODUCTION.....	48
EXPERIMENT 1: PSYCHOLOGICAL DIMENSIONS OF ARCHITECTURAL EXPERIENCE .....	59
EXPERIMENT 2: REPLICATION OF PCA RESULTS .....	67
DISCUSSION.....	72
LIMITATIONS.....	78
CONCLUSION .....	79
<b>CHAPTER 4: NATURAL PATTERNS IN ARCHITECTURE .....</b>	<b>81</b>
INTRODUCTION.....	81
ADAPTABILITY AND NATURALNESS .....	81
THE THEORY OF NATURAL STRUCTURE .....	86
CONCLUSION .....	105
<b>CHAPTER 5: PSYCHOLOGICAL RESPONSES TO NATURAL PATTERNS IN ARCHITECTURE .....</b>	<b>107</b>
INTRODUCTION.....	107
EXPERIMENT 1: IDENTIFYING NATURE-LIKE PATTRNS IN ARCHITECTURE .....	117
EXPERIMENT 2: DOES NATURALNESS OF BUILDINGS INFLUENCE SIMILARITY PERCEPTIONS? .....	127
EXPERIMENT 3: DOES NATURALNESS OF BUILDINGS INFLUENCE PREFERENCE? .....	140
EXPERIMENT 4: WHY ARE NATURAL PATTERNS PREFERRED?.....	145

DISCUSSION .....	148
LIMITATIONS .....	155
CONCLUSION .....	157
<b>SUMMARY AND CONCLUSIONS.....</b>	<b>158</b>
<b>REFERENCES .....</b>	<b>168</b>
<b>APPENDIX A: SUPPLEMENTARY MATERIALS FOR CHAPTER 3 .....</b>	<b>207</b>
NEURAL CORRELATES OF FLUENCY, FASCINATION, AND HYGGE .....	209
<b>APPENDIX B: SUPPLEMENTARY MATERIALS FOR CHAPTER 5.....</b>	<b>210</b>
BUILDING FUNCTION ANALYSES .....	212
<b>APPENDIX C: PILOT STUDY OF NATURAL STRUCTURE AND WELLBEING IN CAMBRIDGE RESIDENTIAL HALLS ..</b>	<b>213</b>
INTRODUCTION.....	213
METHODS .....	213
RESULTS .....	215

# Figures

<b>FIGURE 1.1:</b> THE WELLBEING SPECTRUM .....	8
<b>FIGURE 1.2:</b> THE WELLBEING CYCLE.....	9
<b>FIGURE 1.3:</b> SHIFTING THE WELLBEING SPECTRUM .....	13
<b>FIGURE 1.4:</b> PRIMARY DRIVERS OF WELLBEING. ....	14
<b>FIGURE 1.5:</b> HIGH-DENSITY NEIGHBORHOODS (HEALTHY VS. UNHEALTHY) .....	19
<b>FIGURE 1.6:</b> GESTALT TRIANGLE .....	21
<b>FIGURE 1.7:</b> DENSITY REVEALS LITTLE ABOUT ENVIRONMENTAL QUALITY .....	22
<b>FIGURE 1.8:</b> AESTHETIC RESPONSES TO ARCHITECTURE MEDIATE INFLUENCE OF DESIGN ON WELLBEING. ....	25
<b>FIGURE 2.1:</b> THE VITRUVIAN TRIAD .....	28
<b>FIGURE 2.2:</b> THE AESTHETIC TRIAD .....	30
<b>FIGURE 3.1:</b> THE <i>AESTHETIC TRIAD</i> AND ASSOCIATED PSYCHOLOGICAL DOMAINS. ....	50
<b>FIGURE 3.2:</b> ARCHITECTURAL STIMULI .....	59
<b>FIGURE 3.3:</b> CORRELATION MATRIX OF 16 ORIGINAL PSYCHOLOGICAL DIMENSIONS. ....	63
<b>FIGURE 3.4:</b> PCA FACTOR LOADINGS.....	65
<b>FIGURE 3.5:</b> 3-WAY FACTORIAL ANOVA RESULTS (EXPERIMENT 1).....	66
<b>FIGURE 3.6:</b> CORRELATION MATRIX OF 9 PSYCHOLOGICAL VARIABLES FROM EXPERIMENT 2. ....	69
<b>FIGURE 3.7:</b> FACTOR LOADINGS ON THE THREE PRINCIPAL COMPONENTS FOLLOWING OBLIMIN ROTATION.....	70
<b>FIGURE 3.8:</b> 3-WAY FACTORIAL ANOVA RESULTS (EXPERIMENT 2).....	71
<b>FIGURE 4.1:</b> ADAPTABLE VS. INFLEXIBLE OFFICE .....	82
<b>FIGURE 4.2:</b> THE SALUTORY NATURAL LANDSCAPE OF THE SCOTTISH HIGHLANDS .....	84

<b>FIGURE 4.3:</b> (L) "MAN-MADE" NATURAL ENVIRONMENT VS. "NATURAL" MAN-MADE ENVIRONMENT. ....	85
<b>FIGURE 4.4:</b> (L) "UNATTRACTIVE URBAN" VS. "ATTRACTIVE URBAN" .....	86
<b>FIGURE 4.5:</b> FIFTEEN PATTERNS OF NATURAL STRUCTURE.....	88
<b>FIGURE 4.6:</b> BOUNDARIES IN NATURE .....	90
<b>FIGURE 4.7:</b> LEVELS OF SCALE IN NATURE .....	91
<b>FIGURE 4.8:</b> LOCAL SYMMETRIES IN NATURE .....	92
<b>FIGURE 4.9:</b> BOUNDARIES IN ARCHITECTURE (1) .....	93
<b>FIGURE 4.10:</b> BOUNDARIES IN ARCHITECTURE (2) .....	93
<b>FIGURE 4.11:</b> LEVELS OF SCALE IN ARCHITECTURE (1) .....	94
<b>FIGURE 4.12:</b> LEVELS OF SCALE IN ARCHITECTURE (2) .....	95
<b>FIGURE 4.13:</b> LOCAL SYMMETRIES IN ARCHITECTURE (1) .....	95
<b>FIGURE 4.14:</b> LOCAL SYMMETRIES IN ARCHITECTURE (2) .....	96
<b>FIGURE 4.15:</b> NATURAL GENERATION VS. ARTIFICIAL FABRICATION (1) .....	98
<b>FIGURE 4.16:</b> NATURAL GENERATION VS. ARTIFICIAL FABRICATION (2) .....	99
<b>FIGURE 4.17:</b> (L) COMPLEX ORGANIZATION VS. SIMPLISTIC REPETITION .....	101
<b>FIGURE 4.18:</b> THE "DEGREE OF LIFE" SPECTRUM.....	102
<b>FIGURE 4.19:</b> BOUNDARIES IN ARCHITECTURE (3) .....	104
<b>FIGURE 4.20:</b> (L) SINGLE-USE DEVELOPMENT VS. MULTI-USE DEVELOPMENT .....	105
<b>FIGURE 5.1:</b> THE CORINTHIAN COLUMN'S BIOLOGICALLY-INSPIRED DESIGN .....	110
<b>FIGURE 5.2:</b> SAGRADA FAMILIA AND TAJ MAHAL .....	111
<b>FIGURE 5.3:</b> ARTIFICIAL STRUCTURE IN BRASILIA AND CAMBRIDGE UNIVERSITY DORMITORY.....	112

<b>FIGURE 5.4:</b> FIFTEEN PATTERNS OF NATURAL STRUCTURE (ALEXANDER, 2002) .....	113
<b>FIGURE 5.5:</b> EXAMPLES OF SCALING MEASURES .....	122
<b>FIGURE 5.6:</b> EXAMPLES OF CONTRAST MEASURES.....	123
<b>FIGURE 5.7:</b> CORRELATION MATRICES OF IMAGE STATISTICS FOR INTERIORS AND EXTERIORS .....	124
<b>FIGURE 5.8:</b> IMAGE STATISTICS PREDICTING NATURALNESS. ....	127
<b>FIGURE 5.9:</b> SCREE PLOTS OF MDS ANALYSIS.....	131
<b>FIGURE 5.10:</b> PLOTTED RESULTS OF MDS DIMENSIONS FOR INTERIORS A .....	132
<b>FIGURE 5.11:</b> PLOTTED RESULTS OF MDS DIMENSIONS FOR INTERIORS B .....	133
<b>FIGURE 5.12:</b> PLOTTED RESULTS OF MDS DIMENSIONS FOR EXTERIORS A.....	134
<b>FIGURE 5.13:</b> PLOTTED RESULTS OF MDS DIMENSIONS FOR EXTERIORS B .....	135
<b>FIGURE 5.14:</b> CORRELATIONS OF DIMENSION 1 WEIGHTS WITH PERCEIVED NATURALNESS .....	136
<b>FIGURE 5.15:</b> PREFERENCE VS. NATURALISTIC SCALING AND CONTRAST PATTERNS .....	144
<b>FIGURE 5.16:</b> CORRELATIONS BETWEEN MODELED NATURALNESS AND ORDER, COMFORT, EXCITEMENT....	147
<b>FIGURE A1:</b> EXPERIMENTAL STIMULI (LOW CEILINGS) .....	207
<b>FIGURE A2:</b> EXPERIMENTAL STIMULI (HIGH CEILINGS) .....	208
<b>FIGURE A3:</b> NEURAL CORRELATES OF 3 PSYCHOLOGICAL DIMENSIONS .....	209
<b>FIGURE B1:</b> EXPERIMENTAL STIMULI (INTERIORS) .....	210
<b>FIGURE B2:</b> EXPERIMENTAL STIMULI (EXTERIORS) .....	211
<b>FIGURE C1:</b> PHOTOS OF CAMBRIDGE HOUSES.....	214



## Tables

<b>TABLE 3.1:</b> SUMMARY OF STIMULUS DISTRIBUTION WITHIN EACH IMAGE BLOCK .....	61
<b>TABLE 3.2:</b> RATING GROUPS FOR PSYCHOLOGICAL RATING SCALES. ....	61
<b>TABLE 3.3:</b> PROMPTS AND END ANCHORS OF 7-POINT RATING SCALES FOR THE PSYCHOLOGICAL DIMENSIONS. ....	62
<b>TABLE 3.4:</b> PCA FACTOR LOADINGS (EXPERIMENT 1) .....	65
<b>TABLE 3.5:</b> PCA FACTOR LOADINGS (EXPERIMENT 2) .....	70
<b>TABLE 5.1:</b> REGRESSION OF NATURALNESS RATINGS VS. IMAGE FEATURES (INTERIORS) .....	126
<b>TABLE 5.2:</b> REGRESSION OF NATURALNESS RATINGS VS. IMAGE FEATURES (EXTERIORS) .....	126
<b>TABLE 5.3:</b> DIMENSION 1 WEIGHTS VS. MODELED NATURALNESS AND EXPLICIT NATURE (INTERIORS A) .....	138
<b>TABLE 5.4:</b> DIMENSION 1 WEIGHTS VS. MODELED NATURALNESS AND EXPLICIT NATURE (INTERIORS B) .....	138
<b>TABLE 5.5:</b> DIMENSION 1 WEIGHTS VS. MODELED NATURALNESS AND EXPLICIT NATURE (EXTERIORS A) .....	138
<b>TABLE 5.6:</b> DIMENSION 1 WEIGHTS VS. MODELED NATURALNESS AND EXPLICIT NATURE (EXTERIORS B) .....	138
<b>TABLE 5.7:</b> DIMENSION 1 WEIGHTS VS. NATURALISTIC SCALING AND CONTRAST (INTERIORS A) .....	139
<b>TABLE 5.8:</b> DIMENSION 1 WEIGHTS VS. NATURALISTIC SCALING AND CONTRAST (INTERIORS B) .....	139
<b>TABLE 5.9:</b> DIMENSION 1 WEIGHTS VS. NATURALISTIC SCALING AND CONTRAST (EXTERIORS A) .....	139
<b>TABLE 5.10:</b> DIMENSION 1 WEIGHTS VS. NATURALISTIC SCALING AND CONTRAST (EXTERIORS B) .....	139
<b>TABLE 5.11:</b> PREFERENCE RATINGS VS. MODELED NATURALNESS AND EXPLICIT NATURE (INTERIORS) .....	143
<b>TABLE 5.12:</b> PREFERENCE RATINGS VS. MODELED NATURALNESS AND EXPLICIT NATURE (EXTERIORS) .....	143
<b>TABLE 5.13:</b> PREFERENCE RATINGS VS. NATURALISTIC SCALING AND CONTRAST (INTERIORS) .....	143
<b>TABLE 5.14:</b> PREFERENCE RATINGS VS. NATURALISTIC SCALING AND CONTRAST (EXTERIORS) .....	144
<b>TABLE 5.15:</b> IMAGE-RATING TASK ASSIGNMENT BY GROUP .....	146

<b>TABLE B1:</b> DEVIATION CONTRASTS FOR NATURALNESS VS. BUILDING FUNCTION (INTERIORS) .....	212
<b>TABLE B2:</b> DEVIATION CONTRASTS FOR PREFERENCE VS. BUILDING FUNCTION (INTERIORS) .....	212
<b>TABLE B3:</b> DEVIATION CONTRASTS FOR NATURALNESS VS. BUILDING FUNCTION (EXTERIORS) .....	212
<b>TABLE B4:</b> DEVIATION CONTRASTS FOR PREFERENCE VS. BUILDING FUNCTION (EXTERIORS) .....	212
<b>TABLE C1:</b> RESULTS OF DEGREE OF LIFE SURVEYS .....	216
<b>TABLE C2:</b> RESULTS OF SUBJECTIVE VITALITY, WEMWBS, AND RESIDENTIAL SOCIAL SURVEYS .....	217

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I couldn't have completed this project without the support and encouragement of my dad, Jeff, and my late mother, Catherine. Thank you for always believing in me and for pushing me forward. Thanks to Joel, Ron, and David for your friendship and for our many conversations about architecture and residential communities at Amherst. Those conversations were the source of my interest in understanding the psychological impact of architectural design, and they were the wellspring of this thesis. Finally, many thanks to the Cambridge Trusts, the Smith Family Fund, and the TKF Foundation, whose generous funding supported this research.

## Collaborations

Chapter 2 of this thesis was written in collaboration with Oshin Vartanian at the University of Toronto and Anjan Chatterjee at the University of Pennsylvania. I wrote the first draft of the manuscript of this chapter, which then went through several rounds of editing among the three authors. I am responsible for most of the written content in this chapter. However, my collaborators played an important role in editing my draft, in shaping the structure of the argument, and in clarifying neuroscience-related technical points. The experiments and analyses in Chapter 5 were carried out in collaboration with Omid Kardan, Hiroki Kotabe, Jason Steinberg, and Marc Berman at the University of Chicago; Michael Hout, Arryn Robbins, and Justin MacDonald at the University of New Mexico; and Gregor Hayn-Leichsenring at the University of Pennsylvania. The specific contributions of these collaborators are cited within this chapter, and my personal contributions to Chapter 5 are explained in detail below. I am solely responsible for all of the other experimental work and written content of this thesis.

Although some of the experimental work in Chapter 5 was carried out by my collaborators, I am responsible for the majority of the intellectual content, experimental design, and statistical analysis, as well as all of the written content of this chapter. Before meeting Dr. Berman, I read his 2014 paper and saw parallels between his work and Alexander's patterns. Specifically, I noticed that some of the low-level visual features he had found to be associated with naturalness in outdoor scenes (i.e., Edge Density, sdBrightness, sdHue, sdSaturation) were closely related to Alexander's proposed patterns of naturalistic architecture. I devised the main research questions of this chapter on my own and then approached Dr. Berman by email in early 2016 to see if he would be interested in collaborating with me to run experiments testing these questions. He invited me to meet him in person, and in the summer of 2016 I flew to Chicago and gave a presentation to twelve members of his lab (the Environmental Neuroscience Lab) describing my proposed project. The presentation and ensuing discussion helped clarify the approach we would take of measuring Alexander's patterns using image statistics and assessing naturalness and preference ratings using the Amazon Mechanical Turk online survey interface.

Although the research methods of this study were similar to those of Dr. Berman's 2014 paper on low-level visual features predicting perceptions of naturalness in outdoor landscapes

(Berman et al., 2014), the context (i.e. architectural scenes) was different, and so I had to generate an entirely new stimulus set. To do this, I spent the next month or so collecting stimuli from the study (240 images in total), and I made decisions such as a) how to counterbalance the stimuli to control for building function, b) which types of building function to include, c) how to minimize the amount of vegetation present in stimuli, d) whether to study interiors or exteriors (we ended up sampling both), e) how to standardize the images (e.g. excluding images with people and vegetation; taking Google Street View photos at a certain distance from the façade), and f) how to control for the remaining vegetation (using the Explicit Nature variable). I collected these stimuli on my own in my laboratory at the University of Pennsylvania in Philadelphia, where I was working at the time. The only input from my collaborators for this part of the project was the occasional check-in over email or Skype.

Once the stimuli were ready, the next step in the process was to collect participants' ratings of the stimuli on our psychological scales of interest (naturalness, preference) using Qualtrics and Amazon Mechanical Turk. At first, I was expecting to execute this part of the project on my own, as I had recently designed and completed similar experiments for my work at University of Pennsylvania. However, my collaborators at University of Chicago felt that it would be less complicated if they administered the surveys using their lab's MTurk account, for the simple reason that they had external funding from the TKF Foundation to pay the participants (and I did not). This seemed like a logical plan, so we decided that they would collect the online data using my stimulus set. The survey design process, however, was a collaborative effort. Over the course of several email exchanges and Skype conversations, we decided to conduct separate surveys for interior vs. exterior image sets, as well as for each question type (i.e. naturalness vs. preference), and together we decided on the specific wording of the question prompts (e.g. *"how artificial or natural does this building look to you?"*) and the Likert scale anchors (e.g. *"artificial"* to *"natural"*).

Around this time, I also came up with the idea of adding several more rating scales to our study in order to understand the more nuanced psychological correlates of natural patterns in architecture. I proposed adding three additional scales (order, comfort, and excitement) based on the results of the three principal components identified in the Principal Components Analysis in Chapter 3 of this thesis. For these additional rating scales, I also helped design the

experimental instructions, question prompts, and Likert scale anchors, over email and Skype with my colleagues at University of Chicago. Once we had finalized the survey design, my colleague, Hiroki Kotabe, sent out the surveys via Amazon Mechanical Turk.

The next step in the process was to measure Alexander's patterns by quantifying low-level visual features of the images I had collected. In order to be able to compare our results with those of Dr. Berman's 2014 study, we decided to measure the same low-level visual features that they had measured in their 2014 study. My colleague, Omid Kardan, offered to measure these low-level visual features using the same algorithms in MatLab that he had used for several previous studies. Most of these measurements can be executed using standard functions in MatLab. I did not have a copy of the program at the time and was not financially capable of obtaining a copy, so I accepted Omid's offer to measure these features using his copy of MatLab. One of the features (Entropy) required using a non-standard function that Dr. Berman and his colleagues had developed for a previous study, as described on p. 119. I proposed adding one additional measure, Fractal Dimension, in order to better capture Alexander's *Levels of Scale* pattern. For this measurement, Omid and I chose to use the box-counting method on the edge maps of the images, as described on p. 119.

After collecting participant ratings and measuring low-level visual features, Hiroki and Omid sent me the raw data files. I then cleaned these data files, combined them into one file, and executed all of the statistical analyses reported in Experiments 1, 3, and 4 of Chapter 5. I carried out all of the linear regressions for these experiments using R Studio, JASP, and SPSS, and I calculated the Explicit Nature variable using Adobe Photoshop (as described on p. 124).

After we had collected and analyzed the data for Experiments 1, 3, and 4, Dr. Berman and I discussed the idea of adding an MDS experiment to the study to see if latent similarity perceptions would be predicted by naturalness ratings and by naturalistic architectural patterns of Scaling and Contrast. We wanted to know if people would "see" natural patterns in the images, and use these patterns to organize the images, without being prompted to do so. Dr. Berman had previously collaborated on several MDS experiments with Dr. Hout and Dr. MacDonald at New Mexico State University, so he invited them to join our project. For this project, Dr. Hout had already written an algorithm in e-prime that accommodated our MDS experimental design, so we set up the experiment using this algorithm. I divided the

images into four subsets for the MDS experiments. Since we were now collaborating with researchers based at three different universities, we decided to diversify the participant pool by running the study at two separate institutions and combining the results.

I offered to run participants at University of Pennsylvania. However, Dr. Berman had funding available to run participants at University of Chicago (and I did not), and Dr. Hout had set up a system in his department whereby undergraduate psychology students could sign up to participate in experiments in exchange for course credit (and such a system was not in place at University of Pennsylvania). We therefore decided that it was most practical to run the MDS study at University of Chicago and New Mexico State University. Arryn Robins (one of Dr. Hout's PhD students) took charge of data collection at New Mexico State University, and Omid Kardan and Jason Steinberg were responsible for collecting data at University of Chicago.

After the data collection was completed, I carried out the data analysis for Experiment 2 and created all the figures and regression analyses in the "results" section of Experiment 2. I then wrote the first draft of the manuscript for the journal paper that served as the template for Chapter 5 of this thesis. Although the manuscript went through several rounds of editing, I was responsible for all of the written content presented in Chapter 5. Notably, although the experiments of Chapter 5 involved similar research methods as Dr. Berman's 2014 paper (Berman et al., 2014), the literature review for the chapter was substantially different from the previous paper. The literature review of Chapter 5 discusses the psychological implications of naturalistic patterns in architecture, whereas the brief literature review of Dr. Berman's 2014 paper focuses on the psychological benefits of exposure to natural (i.e., non-architectural) environments. The latter is a widely investigated topic in environmental psychology, whereas the former has received scant attention from researchers. Thus, it represents a unique contribution to the literature.

To summarize my personal contribution to Chapter 5, I formulated the research questions, wrote the literature review, approached Dr. Berman about collaborating on the experiments, decided which experiments to carry out, created the 240 image stimulus set for Experiments 1, 3, and 4, wrote the survey prompts and experimental instructions for Experiments 1, 3, and 4, created the stimulus sets for Experiment 2, organized and analyzed all the data for

Experiments 1-4, wrote up the methods and results for Experiments 1-4, designed all figures and tables in the chapter, and wrote the introduction, discussion, and conclusion to the chapter. As mentioned in the first paragraph of this section, I was responsible for all of the work other than the specific experimental collaborations described in the footnotes of Chapter 5. Furthermore, I am the first author on the manuscript associated with this chapter, which is currently under review at a peer-reviewed journal and is available for viewing online at <https://psyarxiv.com/brquh/>.



## **Dissemination of this research**

Chapter 2 of this thesis was published in September 2017 in the *Journal of Cognitive Neuroscience* with the title, “Buildings, beauty, and the brain: a neuroscience of architectural experience.” A manuscript corresponding to Chapter 3 is in preparation and will be submitted for publication in the summer of 2018 with the title, “Psychological and neural responses to architectural interiors.” The results of this chapter were also presented in Boston in March 2018 at the 25<sup>th</sup> annual meeting of the Cognitive Neuroscience Society. A manuscript corresponding to Chapter 5 was submitted in the summer of 2018 to the *Journal of Environmental Psychology* with the title “Psychological responses to natural patterns in architecture.” The results of this chapter were also presented orally at the 3<sup>rd</sup> biennial meeting of the *Academy of Neuroscience for Architecture* at the Salk Institute in La Jolla, California, in September 2018. I am the first author on all of these papers.

## Personal Journey

The roots of this dissertation formed in December, 2014 when I came across Christopher Alexander's *Nature of Order* books in the basement of the Architecture Library at Cambridge. These books transformed the way I thought about the physical environment and motivated me to test Alexander's ideas firsthand. As further explained in Chapter 4, Alexander's books describe a series of fifteen nature-like patterns in architecture that are associated with what he calls "living structure." Furthermore, he proposes that people feel more "alive" and "whole" in the presence of buildings and places with higher degrees of "living structure," and that this environmental quality enhances the wellbeing of individuals and communities. While I found these ideas compelling on an intuitive level, they had never been experimentally tested or validated. And so, at the beginning of my PhD journey, I set out to test some of Alexander's fundamental claims using empirical research methods.

At first, I wanted to test directly whether buildings with a higher degree of living/natural structure enhanced social communities and occupant wellbeing. The pilot study of my first-year report (see Appendix C) reflected this approach. In that study, I measured occupant wellbeing and community strength in two graduate dormitories at Hughes Hall, Cambridge. These two buildings housed similar populations of graduate students but differed greatly in the degree of living/natural structure. Residents of each building had lived there for about a year. I predicted that residents of the building rated as having a higher degree of living/natural structure would report higher degrees of subjective well-being, vitality, and would score higher on measures of community strength.

For this study, the perceived amount of living/natural structure in each building was measured by showing participants side-by-side photographs of comparable spaces in each building (e.g. hallway, bedroom, foyer, front door, window) and by asking two questions: 1) "which building feels more alive?" and 2) "which building feels more natural?" Occupant wellbeing was measured using the Warwick-Edinburgh Mental Well-Being Scale (Tennant et al., 2007) and the Subjective Vitality Survey (Ryan et al., 2010). Community strength was measured with the Residential Social Survey (Coburn, 2013). As predicted, occupants living in the building that was rated as having a greater degree of living/natural structure reported significantly higher levels of well-being and vitality, and measures of community strength

were also significantly higher in that building. The results of this study were encouraging and motivated me to further pursue experimental work testing Alexander's theories.

Despite the promising findings of this pilot study, I received important feedback from the examiners of my first-year report that shaped the development of my research methods for the experiments presented in Chapters 3 and 5 of this dissertation. First, the decision to compare just two buildings was viewed as quite limited, as it resulted in a prohibitively small sample size and increased the likelihood that confounding factors other than architectural design had influenced the results. Secondly, the method of measuring the degree of living/natural structure in each building was also limited, as it relied exclusively on self-reported assessments of these architectural properties and did not in any way link the reported assessments to objectively measurable architectural features. This made it difficult to prove (beyond the author's own subjective judgement) that the wellbeing-promoting building actually embodied the nature-like patterns described by Alexander. It was therefore impossible to link these patterns to perceptual or behavioral outcomes in any objective manner.

A few months after defending my first-year report, I came across a research paper by Dr. Marc Berman at the University of Chicago that seemed highly relevant to the research questions I was trying to tackle in my PhD. In this paper (Berman et al., 2014), Dr. Berman and his colleagues investigated whether perceptions of naturalness in outdoor scenes could be reliably predicted by computationally-measured low-level spatial and color features of the scenes. The basic motivation of this work was that "natural" environments have consistently been found to improve psychological experience and well-being, and so the authors wanted to see whether visual features associated with naturalness could be quantified and, eventually, superimposed onto built spaces to enhance psychological outcomes. The premise of this work aligned closely with my own research questions. Intriguingly, several of the visual features that Dr. Berman and his colleagues found to be associated with naturalness in outdoor scenes were also closely related to the nature-like visual patterns that Alexander had theorized as being indicative of natural/living architectural structure.

The research methods of this paper made me realize that I could potentially measure some of Alexander's natural patterns using computational analysis of low-level image features.

Furthermore, Dr. Berman's method of analyzing psychological response to images offered a way to overcome many of the additional limitations of my first-year pilot study. Analyzing images would enable me to obtain much larger sample sizes of architectural spaces in order to test whether Alexander's proposed architectural patterns were actually perceived as "natural," which was a basic foundational premise that my first-year pilot study was unable to verify. Furthermore, I realized that using image analysis would enable me to achieve much greater statistical power in testing acute psychological responses to natural patterns in architecture. In light of these realizations, I approached Dr. Berman and began a collaboration with his research group that resulted in the experiments presented in Chapter 5 of this thesis, in which we measured Alexander's patterns using image statistics and investigated how these patterns related to perceptions of naturalness and other dimensions of psychological experience. This collaboration also resulted in the writing of a manuscript closely related to Chapter 5, entitled "Psychological responses to natural patterns in architecture." The manuscript is currently under review for publication in a peer-reviewed journal.

After submitting my first-year report, I also began to realize that Alexander's descriptions of psychological experiences associated with exposure to natural patterns in architecture, such as increased feelings of "wholeness" and "vitality," were somewhat vague and nonspecific. I wanted to develop a more nuanced analysis of these types of mental experiences using more conventional psychological research methods than Alexander had used in his books. Around the time that I encountered Dr. Berman's paper, I met Dr. Anjan Chatterjee, a neurologist at the University of Pennsylvania who was working on a series of projects investigating neuroscientific responses to architectural design. I told Dr. Chatterjee about my interest in Alexander's work and my desire to investigate whether natural patterns in architecture invoke specific types of mental states.

After a few meetings, Dr. Chatterjee and I realized that the mental states of interest would be difficult to identify given that the existing literature on the psychology of architecture was somewhat limited and fairly disorganized from a theoretical standpoint. Specifically, there existed at the time no coherent neuroscientific framework outlining the neural systems that are most engaged when people encounter architectural spaces. This gap in the literature led us to develop over the next year or so the aesthetic triad model of architectural experience, which is the proposed neural framework outlined in Chapter 2 of this thesis.

Furthermore, Dr. Chatterjee and I discussed in our initial meetings the lack of consistency in research on the psychology of architecture. Specifically, there existed at the time no agreed-upon framework of the key psychological dimensions of architectural experience. This gap in the literature was highly relevant to my research on Alexander's work, as I wanted to test psychological responses to Alexander's proposed natural patterns using empirically verified rating measures. These early conversations eventually led me to undertake the research summarized in Chapter 3 of this thesis, which resulted in the identification of three psychological dimensions of architectural experience reported in that chapter: *fluency*, *fascination*, and *hygge*<sup>2</sup>. These dimensions, in turn, provided the theoretical framework for testing the psychological correlates of Alexander's natural patterns in Chapter 5, Experiment 4 of this thesis.

An important methodological question to address throughout the research process was whether to focus on a single building typology, as is often the case in architectural research, or to undertake a more general investigation of the built environment across multiple building typologies. During the first year, I leaned towards a single-typology approach, as I had undertaken for my undergraduate and Masters' dissertations, both of which investigated college residential dormitory design. This was also the approach I took for the first-year pilot study discussed in Appendix C, which compared two graduate university dormitories.

However, I found this approach quite limiting in light of the main research questions of the thesis, which explored the influence of aesthetic qualities of architecture on acute psychological experience. An image set representing only a single building typology is likely to contain less diversity of aesthetic features than in image set derived from a cross-section of many building typologies, and I did not want to constrain the variance in aesthetic features (the primary independent variable of interest) in this way. Such an approach would limit the external validity of the findings to the specific typology studied. I also had no a priori reason to believe that aesthetic features would be more relevant to psychological experience for any one particular building typology compared to any other. It seemed more logical to me that

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<sup>2</sup> *Hygge* is a Danish word that describes "a feeling of coziness, warmth, and togetherness" (Wiking, 2017, p. 25) that is often felt in the presence of intimate spaces and social settings. This concept is further explained in the "discussion" section of Chapter 3.

the relationship between aesthetic features and psychological experience would be independent of building typology. In fact, including a variety of building typologies in the research enabled me to test this very question: to what extent does typology influence aesthetic responses to architectural scenes? This question is tested in the experiments of Chapter 5, where images are counterbalanced across six different building typologies. As the results of Tables B1-B4 of Appendix B indicate, building typology did not have a significant effect on naturalness or preference ratings for either interior or exterior images in that study, and the effects of natural patterns on aesthetic preference were statistically significant across all six building typologies. These interesting findings would not have emerged had the study been limited to a single building typology.

Investigating only a single building typology also would have been inconsistent with the approach of Alexander (2002), whose work formed the foundation of this thesis. His theories about the effects of natural patterns on occupant experience are not limited to a single building typology. On the contrary, he argues that the degree of living/natural structure in architecture has important implications for human experience across all classes of building typologies and at many levels of scale (e.g. room, building façade, street, neighborhood). The approach of isolating a single typology would test his ideas only in a very limited sense. The multiple-typologies approach for Chapter 3 was also consistent with published neuroaesthetics research that motivated the studies presented in that chapter (see, for instance, Vartanian et al., 2013 & 2015). For all of these reasons, I chose to include a cross-section of building functions in my image sets instead of focusing on a single typology.

In summary, my independent research during the first year of the PhD resulted in a keen interest in Christopher Alexander's proposed patterns of living/natural structure and their effect on occupant well-being and strength of residential communities. This year of research inspired the content of Chapters 1 and 4 of this thesis and motivated the pilot experiment summarized in Appendix C. However, key limitations of the pilot study that were pointed out during my first-year examination inspired me to take a different methodological approach, one that examined acute psychological responses to a large number of architectural images rather than self-reported wellbeing outcomes of occupants living in a more limited number of actual buildings. I undertook this new approach in collaboration with Dr. Berman at the University of Chicago and Dr. Chatterjee at the University of Pennsylvania, in whose lab I

worked during years two and three of my PhD. The research I completed during these final two years resulted in the content of Chapters 2, 3, 5, and Appendices A and B of this thesis.

# **General Introduction**

## **Summary of research**

People today spend most of their lives in buildings. The design of the built environment can impact mood, behavior, and our overall sense of wellbeing. The evidence discussed in Chapter 1 suggests that the perceived *beauty* of an environment may influence wellbeing more than any single design variable considered in isolation, but this topic has received little scientific attention to date. Recently, researchers have leveraged empirical methods of neuroscience and psychology to identify aesthetic features of architecture that support positive psychological experiences. However, this line of inquiry faces persistent challenges in terms of a) measuring the environment itself and b) evaluating acute psychological responses relevant to design. Indeed, aesthetic features of architecture are difficult to quantify, and the disparate response measures tested in empirical studies remain disconnected from any cohesive psychological or neuroscientific framework. This dissertation addresses both of these gaps in the literature by using image statistics and pattern theory to quantify aesthetic properties of architecture, and by examining how specific neural networks and psychological processes contribute to aesthetic experiences in the built environment. The main research questions and findings from each chapter of the dissertation are summarized below.

## **Chapter 1: Environmental beauty and wellbeing**

Chapter 1 explores the existing literature on wellbeing in the built environment and highlights two gaps in knowledge that the subsequent chapters aim to address: measuring aesthetic qualities of architectural spaces (*measuring the environment*), and evaluating acute psychological responses to architectural design (*measuring the brain*). Previous studies have often investigated how isolated environmental variables impact behavior and health. However, evidence suggests that environmental beauty may contribute to flourishing more than any single design variable considered in isolation (Cooper & Burton, 2014). This chapter proposes using more comprehensive environmental measures, like pattern theory and image statistics, to evaluate aesthetic qualities of architectural design (Ch. 4 & 5). Furthermore, the influence of aesthetic features of architecture on wellbeing is likely mediated by the nervous system, but there has been only limited research to date on the neuroscience and psychology



of architecture. Identifying the complex neural and psychological processes underpinning architectural encounters (Ch. 2 & 3) is therefore an important step towards advancing our understanding of how aesthetic features of architecture influence occupant wellbeing.

## **Chapter 2: A neuroscientific model of architectural experience**

Chapters 2 and 3 of the dissertation address the second gap in knowledge highlighted above, *measuring the brain*. Chapter 2 investigates the neural networks that drive aesthetic experiences in the built environment. Cultures across the globe have long considered *beauty* an integral aspect of human construction. However, the aesthetic dimension of the built environment has been deemphasized in modern building science. This chapter discusses how research methods of neuroscience can be used to study aesthetic experiences in the built environment, following in the footsteps of the nascent discipline of neuroaesthetics. The first neuroscientific model of architectural experience is then proposed. According to this *aesthetic triad* framework, three large-scale neural systems generate aesthetic experiences in the built environment: sensorimotor, emotion-valuation, and knowledge-meaning systems. Architecture engages multiple sensory networks, triggers motor responses such as approach and avoidance, and generates emotional responses via emotion-valuation networks. Meaning-knowledge systems informed by personal experiences, culture, and education also shape one's encounters with the built environment. The chapter concludes by outlining the opportunities and challenges that lie ahead as the neuroscience of architecture develops into a more formal experimental discipline.

## **Chapter 3: Psychological responses to architectural interiors**

In Chapter 3, a pair of experiments are presented investigating the latent dimensions of psychological responses to architectural scenes. Two research questions were addressed in these studies. First, are there principal dimensions of psychological experiences in response to interior architectural scenes? Second, do these psychological dimensions correlate with fundamental aesthetic features of architectural design: ceiling height, enclosure, and curvature? Participants in both experiments rated images of building interiors on semantic differential scales that capture multifaceted aspects of architectural experience. A Principal

Components Analysis (PCA) was conducted on the data, and three components were identified that explained 90% of the variance in ratings: *fluency* (ease with which one organizes and comprehends an architectural scene), *fascination* (the informational richness and interest generated from viewing an architectural scene), and *hygge* (extent to which the architectural scene feels warm and personal).<sup>3</sup> Whereas *fluency* and *fascination* are well-established dimensions in assessing natural scenes and visual art, *hygge* emerged as a new dimension in relation to architectural scenes. In a follow-up study, the PCA results were replicated and an ANOVA revealed that three salient aesthetic features of the architectural scenes – ceiling height, enclosure, and curvature – significantly predicted principal component scores for each of the three psychological dimensions.

## **Chapter 4: Natural patterns in architecture**

In Chapters 4 and 5, the research focus shifts from *measuring the brain* to *measuring the environment*. Chapter 4 introduces two aesthetic qualities of the built environment that have previously been linked to positive psychological experiences: *adaptability* and *naturalness*. Both of these qualities are closely associated with Christopher Alexander’s theory of natural structure (Alexander, 2002). According to this theory, buildings develop nature-like visual patterns in their structure when the methods by which they are constructed resemble the adaptive processes of biological growth. These nature-like construction processes and patterns have been predicted to promote wellbeing in the built environment. This chapter provides a conceptual introduction to Alexander’s theory of natural structure and discusses the ways in which natural patterns in architecture are hypothesized to promote human flourishing.

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<sup>3</sup> *Hygge* is a Danish word that describes “a feeling of coziness, warmth, and togetherness” (Wiking, 2017, p. 25) that is often felt in the presence of intimate spaces and social settings. This concept is further explained in the “discussion” section of Chapter 3.

## **Chapter 5:**

### **Psychological responses to natural patterns in architecture**

Chapter 5 presents a series of experiments motivated by the theories discussed in Chapter 4. These experiments examine whether subjective perceptions of naturalness in architectural scenes are driven by objective visual patterns, and whether these nature-like patterns are robust predictors of similarity evaluations and preference ratings of architectural scenes. In Experiment 1, images statistics were used to operationalize two of Alexander's patterns of natural structure, *Levels of Scale* and *Contrast*, and linear regression models were constructed to see if these patterns predicted subjective naturalness ratings for architectural images. These regression models successfully explained 66% and 52% of the variance in naturalness scores for interior and exterior images, respectively. Visual features related to *Levels of Scale* and *Contrast* accounted for most of the explained variance in naturalness ratings across both image sets, supporting the hypothesis that people associate these patterns with more natural-looking scenes.

In Experiment 2, participants completed an image arrangement task and multidimensional scaling (MDS) analysis was performed on the data to determine the underlying aesthetic dimensions that drove scene similarity judgements. Naturalness ratings explained over half of the variance in MDS Dimension 1 weights, suggesting that people unconsciously relied on latent perceptions of naturalness to evaluate the similarity of architectural scenes. In Experiment 3, participants rated architectural scenes on aesthetic preference, and the naturalness scores of images predicted by low-level visual features alone (Modeled Naturalness) were calculated using the naturalness ratings from Experiment 1. Modeled Naturalness explained 53% and 35% of variance in aesthetic preference ratings for interior and exterior scenes, respectively, when controlling for the amount of vegetation depicted in the scenes. These results suggest that latent perceptions of nature-like features may play an important role in modulating the aesthetic pleasure people derive from viewing architectural scenes. Finally, Experiment 4 revealed that natural patterns were positively associated with feelings of comfort and excitement and negatively associated with perceptions of order, thus demonstrating a conceptual link between the environmental variables measured in Chapter 5 and the psychological dimensions identified in Chapter 3.

## **Summary and conclusions**

The final chapter of the dissertation provides a summary of the conclusions drawn from the theoretical and experimental work presented in Chapters 1-4 and discusses how these conclusions contribute to the literature on the psychology of architecture. Together, these chapters add to a growing body of literature showing how aesthetic qualities of architecture impact psychological experiences. Novel theoretical frameworks are proposed that are useful for contextualizing empirical studies on the psychology and neuroscience of architecture. New methods of image analysis are also used to quantify aesthetic properties of the built environment and to investigate how nature-like patterns in architecture influence psychological experiences. The limitations of this thesis are also addressed in the concluding chapter along with proposals for how these limitations can be addressed in future studies.

# **Chapter 1:**

## **Environmental beauty and wellbeing**

### **Introduction**

The design of the built environments where we live and work can have a meaningful impact on our wellbeing. However, this line of study has had a limited impact to date on architectural practice and planning policy. This chapter reviews past research on wellbeing in the built environment and highlights two gaps in knowledge that have motivated the studies of this dissertation: limitations in how we measure aesthetic features of the built environment (*measuring the environment*), and limitations in how we measure acute psychological responses to design (*measuring the brain*).

Previous research in this field has generally investigated the impact of isolated environmental variables on behavior and health. However, evidence suggests that holistic aesthetic qualities of architecture may contribute to human flourishing more than any single design variable considered in isolation (Cooper & Burton, 2014). To address this gap in the literature, more comprehensive measures of the built environment are proposed, like pattern theory (Alexander, 2002) and image statistics (Berman et al., 2014), in order to evaluate aesthetic qualities of architectural design that may modulate occupant wellbeing.

The influence of aesthetic features of architecture on wellbeing is likely mediated by the nervous system, via acute psychological responses to design. However, there has been limited research to date on the neuroscience and psychology of architecture, and the disparate neuropsychological response measures that have been tested remain disconnected from any cohesive psychological or neuroscientific framework (Chatterjee & Vartanian, 2014; Graham et al., 2015; Eberhard, 2008). Tethering these dependent response variables to theoretical models could help advance our understanding of how short-term aesthetic experiences in the built environment influence long-term wellbeing outcomes.

### **The emerging science of wellbeing**

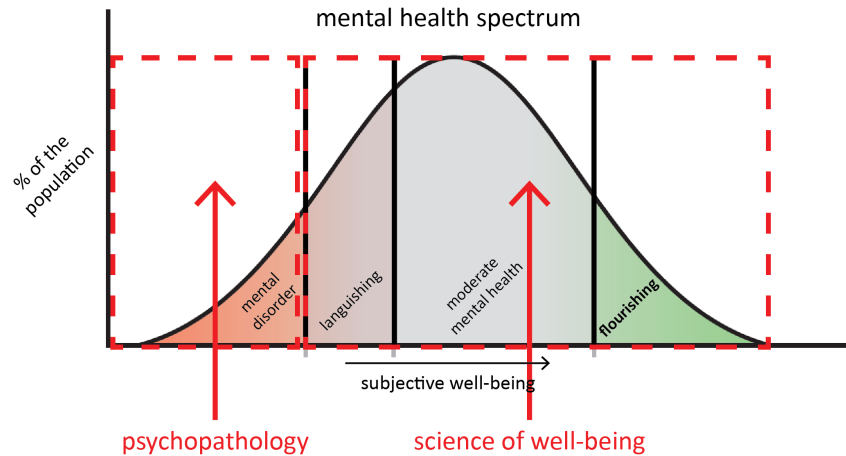
Subjective wellbeing has emerged in recent years as a robust new measurement of mental health. Instead of treating disease, the science of wellbeing aims to help ordinary people live

happier, healthier, and more productive lives and to prevent future cases of mental illness (Diener, Suh, Lucas, & Smith, 1999; Huppert & Cooper, 2014; Ryan & Deci, 2000).

The World Health Organization defines health as “a state of complete physical, mental and social wellbeing and not merely the absence of disease or infirmity” (World Health Organization, 2006, p. 1). Over the past century, however, western medicine has generally followed a pathogenic approach to health focusing on the treatment of disease. Meanwhile, the discipline of clinical psychology has primarily sought to understand mental illnesses like anxiety and depression (Figure 1.1L) (Keyes, 2007; Ryff, 1989a).

The pathogenic perspective has proven appropriate for civilizations threatened by acute and infectious diseases, which have historically accounted for the majority of death and suffering throughout human history (Omran, 2005). Developed societies, however, have more recently undergone epidemiological transitions in which the primary sources of death have shifted away from acute illness and towards chronic and modifiable lifestyle causes (Keyes, 2007). Most people who develop mental illness come from the general, non-diseased population, which exhibits great variations in levels of energy, personal functioning, and happiness (Benyamini, Idler, Leventhal, & Leventhal, 2000). Interventions that prevent new cases require a more subtle understanding of the full spectrum of health conditions in the general population (Figure 1.1R) and clearer insight into the drivers of good health (Huppert, 2009).

The 1960’s witnessed a wave of academic interest in psychological growth (Ryan & Deci, 2001) that celebrated “the individual’s potential for achieving purposes, goals, and other positive forms of higher functioning” (Ryff, 1989a, p. 38). Academic interest in this area of research has resurged since the turn of the millennium, a phenomenon that has coincided with the emergence positive psychology (Ryan & Deci, 2001). Whereas past research focused on how psychosocial stressors weaken physiological systems, positive psychologists are now seeking to understand the extent to which mental wellbeing reduces biological risk (Ryff, Singer, & Love, 2004).



**Figure 1.1: (L) Psychopathology focuses on treating mental illness. (R) The science of wellbeing investigates drivers of positive mental health (Government Office for Science, 2008).**

Convincing evidence has emerged over the past decade linking positive mental functioning to good health. Wellbeing has been proven a robust predictor of future health and longevity even when controlling for current physical conditions (Diener & Seligman, 2004; Ryff et al., 2004). Wellbeing is associated with better functioning of multiple physiological processes, including the immune and cardiovascular systems (Sheldon Cohen, Doyle, Turner, & Alper, 2003; Sheldon Cohen, Doyle, Turner, Alper, & Skoner, 2003; Ryff et al., 2004). In some studies, positive mental health has even been a statistically stronger predictor of mortality and future physiological conditions than negative health measures like disease history, disability, and medication usage (Benyamini et al., 2000).

### What is wellbeing?

Subjective wellbeing describes optimal experience and functioning in human beings (Ryan & Deci, 2001). It is the combination of feeling good (hedonic wellbeing), functioning effectively (eudaimonic wellbeing), and having sufficient psychological resources to do so (Government Office for Science, 2008; Huppert, 2009; Keyes, 2002; Michaelson & Mahony, 2012). While some researchers have focused on one of these three areas more than others, Huppert succinctly explains their interrelated nature, as illustrated in Figure 1.2. “Positive emotions lead to positive cognitions, positive behaviors, and increased cognitive capability, and... positive cognitions, behavior, and capabilities in turn fuel positive emotions” (Huppert, 2009, p. 140). The feedback loop that regulates hedonic affect, eudaimonic behavior, and mental capital highlight the importance of measuring wellbeing as a dynamic construct that accounts for all three dimensions of mental health (Huppert & So, 2013).

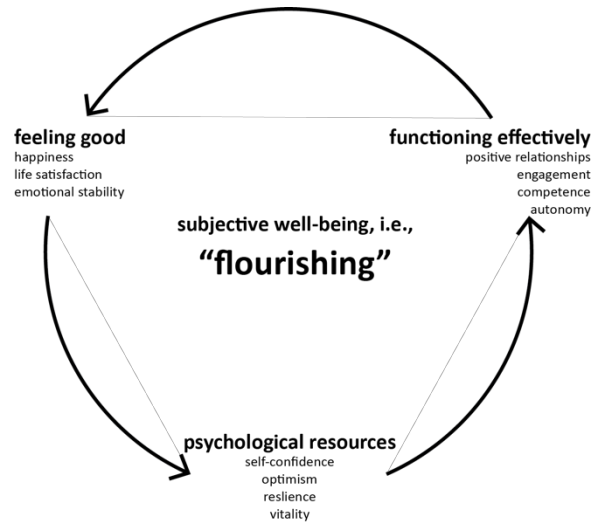


Figure 1.2: The wellbeing cycle (figure designed by the author).

### *Hedonic wellbeing (feeling good)*

Hedonic wellbeing, or emotional wellbeing, represents the magnitude and consistency of an individual’s positive emotional experiences (Keyes, 2002). There are three main dimensions of hedonic wellbeing: the presence of *positive emotions* like pleasure and happiness, the absence of *negative emotions* like anger and fear, and *life satisfaction*, a global judgment of how well one’s life is going (Diener, Wirtz, Tov, & Kim-Prieto, 2010; Huppert & So, 2013; Keyes, 2002).

Positive mood states are an integral aspect of mental health and have been associated with more creative and flexible thinking, a broader focus of attention (Huppert, 2009), and improved immune function (Sheldon Cohen, Doyle, Turner, Alper, et al., 2003; G. F. Solomon, Segerstrom, Grohr, & Kemeny, 1997). One longitudinal study found that positive affect induced by the practice of mindfulness meditation was associated with increases in antibody titers and more robust immune response (Davidson, Kabat-Zinn, Schumacher, & Rosenkranz, 2003). The well-known Nun Study concluded that the relative levels of positive emotions expressed by a group of nuns entering a convent at age 22 predicted their longevity a half-century later, with the happiest young nuns living over nine years longer, on average, than the unhappiest nuns (Danner, Snowdon, & Friesen, 2001).

The consistency of positive emotions, or *emotional stability* (Huppert, 2009), appears to be a more significant indicator of happiness and life satisfaction than the intensity of individual affective experiences (Diener, Sandvik, & Pavot, 2009). Life satisfaction has been a commonly



used global judgment of hedonic wellbeing (Diener & Seligman, 2004), and has been found to be associated with decreased morality rates in the elderly (Parker, Thorslund, & Nordström, 1992) and improved recovery rates after surgery (Kopp et al., 2003).

*Eudaimonic wellbeing (functioning effectively)*

Eudaimonic wellbeing describes how well a person is functioning and highlights behaviors that support sustained mental health (Ryan & Deci, 2001; Waterman, 1993). A number of theoretical constructs have been developed to describe the important behavioral drivers of psychological health (Forgeard, Jayawickreme, Kern, & Seligman, 2011; Huppert & So, 2013; Keyes, 2002; Ryan & Deci, 2000; Ryff, 1989b). The following aspects of human behavior represent key “symptoms” of healthy mental functioning.

*Sense of purpose:* setting goals and having direction in life can contribute to one’s “larger judgment of belonging to and serving something larger than the self ” (Diener & Seligman, 2004, p. 4). Feeling worthless, by contrast, is a common symptom of depression (Huppert & So, 2013).

*Autonomy:* Pursuing self-endorsed or self-motivated goals and behaviours has been theorized to be a stronger source of well-being than striving towards externally-imposed objectives (Jahoda, 1958; Jung, 2001; Ryff, 1989a). Self-determined motivations for behaviour often lead to feelings of enjoyment, interest, and increased vitality, whereas externally-imposed motivations for action have been associated with stress, tension, and diminished energy (Huppert, 2009; Nix, Ryan, Manly, & Deci, 1999; Ryan & Frederick, 1997; Sheldon & Elliot, 1999).

*Environmental mastery:* An individual’s ability to create, choose, or optimize environments and resources tailored to his or her particular circumstances can help a person achieve goals and maximize personal functioning (Jahoda, 1958; Ryff, 1989b).

*Personal growth* describes one’s ability to grow as a person through a continuous developmental process, rather than attempting to achieve a fixed end-state wherein all problems are solved (C. Rogers, 2012; Ryff, 1989b).

*Engagement* has been described as absorption with the present and mindful interest in what one is doing (Diener & Seligman, 2004). Engagement can also be thought of as the opposite

of boredom, a common symptom of depression (Ryff & Singer, 1998). Mindfulness meditation, a practice intended to increase one's engagement with the present, has been shown to stimulate left-brain anterior activation, a pattern associated with positive affect, and to significantly increase antibody titers to the influenza vaccine (Davidson et al., 2003).

*Positive social relationships* and *social support* are central aspects of healthy psychological functioning (Keyes, 2002; Ryan & Deci, 2001; Ryff & Singer, 1998). The number of connections in one's social network of friends, family, colleagues, and neighbors represents one of the strongest predictors of happiness (Brugha et al., 2005; Sheldon Cohen, 2004). Frequency of social engagement in the elderly has also been linked to better physiological functioning and longevity (Menec, 2003).

*Strength of social relationships* has also been positively linked to happiness (Lansford, 2000; Ryff & Singer, 2000) and inversely associated with mortality and suicide rates (Berkman & Syme, 1979; Kweon, Sullivan, & Wiley, 1998). The quality of one's relationships helps regulate allostatic load throughout the life course and may, over time, impact the physiological structure of one's cardiovascular, endocrine, and immune systems (Ryff, Singer, Wing, & Love, 2001; Uchino, Uno, & Holt-Lunstad, 1999). The lack of strong interpersonal ties is a strong predictor of mortality and can be considered a major biomedical risk factor (House, Landis, & Umberson, 1988).

### *Psychological resources*

Psychological resources can be thought of as cognitive assets like *self-esteem*, *resilience*, *optimism*, and *vitality* that help a person feel good and function effectively.

*Optimism* may protect against the risk of coronary heart disease (Kubzansky, Sparrow, Vokonas, & Kawachi, 2001) and has been associated with healthy pulmonary function (Kubzansky, Wright, Cohen, & Weiss, 2002), increased longevity (Maruta, Colligan, Malinchoc, & Offord, 2000; Peterson, 1988), and longer survival rates among cancer patients (Faller, Bulzebruck, Schilling, & Drings, 1997).

*Vitality* describes a person's available supply of physical and mental energy, aliveness, enthusiasm, and vigor (Ryan, Weinstein, Bernstein, & Brown, 2010). In Eastern culture, the Chinese term *chi* and Japanese *ki* refer to a similar concept of positive energy thought to be the source of mental, physical, and spiritual health (Ryan & Frederick, 1997). Vitality has been

linked to improved immune response and resilience to physical stressors, whereas low energy is associated with biological decline (Benyamini et al., 2000; S. Cohen, Alper, Doyle, & Treanor, 2006).

Ryan and Frederick (2007) have suggested that *vitality* may be the best single indicator of overall wellbeing given its strong correlations with both hedonic and eudaimonic wellbeing and positive physiological health outcomes (Nix et al., 1999; Ryan & Frederick, 1997). For instance, reported energy level accounted for 48% of variance in one Self-Assessment of Health study, a measure strongly linked to mortality, recovery from illness, and future physician assessments of health (Benyamini et al., 2000; Dixon, Dixon, & Hickey, 1993).

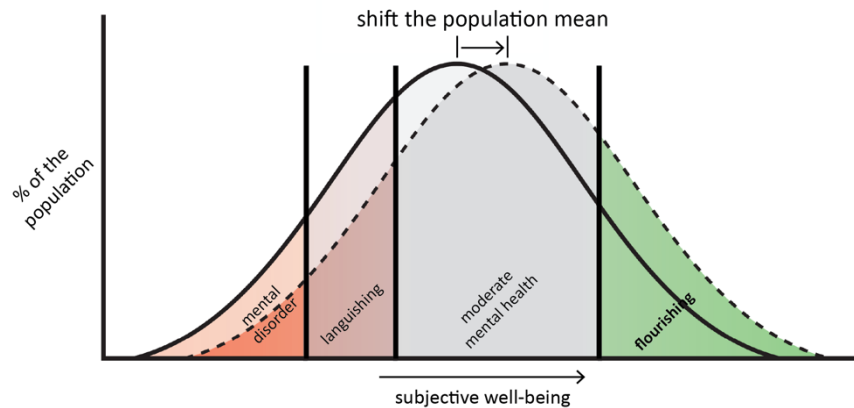
These psychological resources, also referred to as mental capital, can help provide necessary “fuel” for healthy emotional and behavioral patterns. Optimistic students, for instance, may be more likely to develop friendships when transferring to a new school. In turn, positive affect and healthy psychological functioning can also help replenish one’s “reservoir” of mental capital. Making new friends at school, for instance, may increase a student’s available supply of vitality and self-confidence. Hedonism, eudaimonism, and psychological resources are best regarded as three interdependent dimensions of the wellbeing cycle.

### **Flourishing & the wellbeing spectrum**

It has been proposed that any individual’s current level of mental health can be “diagnosed” along a continuous spectrum, from low to high subjective wellbeing, as shown in Figure 1.1 (Anderson, 2014; Huppert, 2009; Keyes, 2002). While people may move up and down the spectrum throughout the course of their lives, they can be described at any one time as experiencing one of four broad states of wellbeing: mental disorder, languishing, moderate mental health, and *flourishing*. Individuals who fall into the highest band, flourishing, generally feel good, function effectively, and have a generous supply of available mental capital. The upper-middle band describes those with moderate wellbeing, and languishing refers to people with poor mental health who are potentially at risk of developing mental illness. The lowest band of the spectrum encompasses people with clinically diagnosed mental disorders like depression and anxiety.

Wellbeing is thought to be normally distributed in population (Huppert, 2009). The majority of the US adult population falls in the “moderate mental health” range of the spectrum, and

only 17% can be described as flourishing (Government Office for Science, 2008). The wellbeing spectrum illustrates the major impact that population-level wellbeing interventions could have on public health. Figure 1.3 reveals how a small upward shift in average wellbeing for a given population, through interventions that improve the lives of many ordinary people, could produce a significant decrease in the number of citizens with mental disorders as well as a large increase in the percentage of the population that is flourishing (Anderson, 2014).



**Figure 1.3: Upward shift in average wellbeing reduces mental disorders and improves overall mental health of population (Government Office for Science, 2008).**

In their Sustainable Happiness Model (SHM), Lyombursky & Sheldon (2005) have proposed three overarching drivers of wellbeing: genetics, intentional behaviors, and environmental factors (Lyubomirsky, Sheldon, & Schkade, 2005). SHM estimates that a person's genetic "set-point," or inherited genetic traits, account for roughly 50% of the variance in subjective wellbeing across individuals, while interdependent behavioral and environmental factors collectively account for the remaining half of variance in wellbeing. Improving the quality of the built environment therefore represents one important population-level intervention that could "shift the spectrum" (Figure 1.3) by incrementally improving subjective wellbeing for a large percentage of the population.

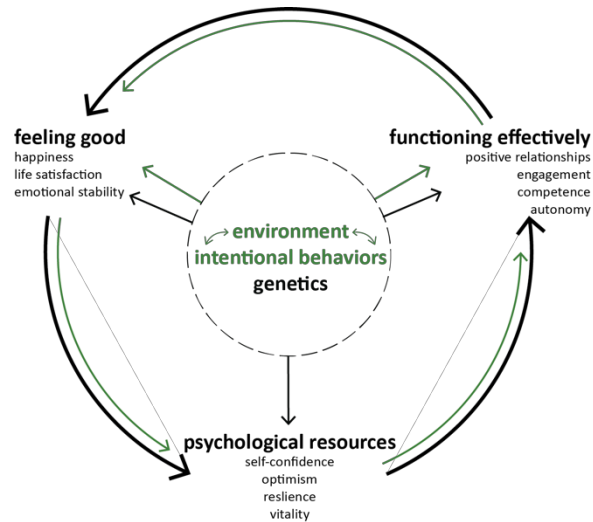


Figure 1.4: Primary drivers of wellbeing.

## Wellbeing and the built environment

### Background

Researchers have increasingly sought to identify features of the built environment that promote flourishing. Studies show that the design of our built environment can modulate how comfortable (Baker & Standeven, 1995; Brager, Paliaga, & De Dear, 2004) or focused (Mehta & Zhu, 2009) we feel in a given moment and can even influence hormonal patterns (Fich et al., 2014; Küller & Lindsten, 1992), speed of recovery from surgery (Ulrich, 1984), and long-term cardiac health (Kardan, Gozdyra, et al., 2015).

Despite the growing popularity of this area of research, however, the evidence that has emerged from it has not been clear, reliable, or consistent enough to have had a widespread impact on architectural design and urban planning (Cooper & Burton, 2014). Two key opportunities could advance this line of research: developing more robust methods for measuring aesthetic qualities of the built environment, and improving our understanding of how design qualities impact short-term psychological experiences.

The majority of past environmental health research has focused on preventing illness rather than promoting flourishing. It is well known, for instance, that indoor and outdoor air pollution can contribute to a variety of respiratory and cardiovascular diseases (Croxford, 2014), that noise pollution can increase blood pressure (Payne, Potter, & Cain, 2014) and alter childhood brain development (Gilbert & Galea, 2014), and that insufficient access to daylight

can negatively affect circadian rhythms and sleep quality (Dutton, 2014). Studies have also highlighted key illness-producing aspects of the physical environment like toxic soil and water sanitation, as well as social problems like crime, crowding, and segregation (Kytä & Broberg, 2014; Steemers, 2015).

The depth of this research has been particularly extensive for certain building typologies, such as learning environments for children. A number of studies, for instance, have demonstrated the prevalence of poor air quality in schools (Lee & Chang, 2000; Kimmel et al., 2000; Khattar et al., 2003) and how this can impact children's health (Ahman et al., 2000; Salleh et al., 2011). For instance, one cross-sectional study of 73 classrooms from 20 public primary schools in Porto, Portugal found that classroom concentrations of certain pollutants such as VOC, acetaldehyde, PM<sub>2.5</sub>, and PM<sub>10</sub> were associated with increased asthmatic respiratory symptoms (e.g. wheezing), even at relatively low exposure levels (Madureira et al., 2015). In another study, poor air quality was also linked to increased rates of absence from school (Rosen & Richardson, 1999). Given that absenteeism is likely to influence educational attainment, it is perhaps self-evident that some metrics of illbeing-focused environmental research, such as respiratory problems, can also relate directly to important metrics of wellbeing, such as learning (Higgins et al., 2005; Woolner et al., 2007). In other words, some of the findings of illbeing-focused research are clearly relevant to the study of wellbeing in the built environment.

This research on environmental causes and consequences of illbeing has led to widespread implementation of health and safety standards and has impacted building design and planning policy across the world. Like the pathological approach to medicine, however, ill-being focused research fails to account for the broad spectrum of behavioral and psychological responses that people experience when they interact with a wide range of environments (Kytä & Broberg, 2014). Just as non-diseased people do not all exhibit signs of flourishing, not all fire-safe and toxin-free buildings promote healthy cognitions and behaviors. In other words, buildings that meet minimum environmental health standards do not necessarily support wellbeing. For instance, while poor air quality in schools may impact absenteeism and consequently learning (Rosen & Richardson, 1999), other environmental features, such as lighting, may influence wellbeing-related outcomes, such as mood and learning (Knez, 1995), without having a measurable impact on traditional measures of ill

health such as respiratory symptoms or illness-related absence from school. In order to promote the design of built environments that are holistically “healthy,” it is clear that researchers must look beyond the traditional disease-centric metrics that foster the design of merely “acceptable” places and identify environmental features and qualities that enable occupants to flourish.

More recently, researchers have taken interest in understanding how the physical environment can actively support human flourishing. Studies have shown that certain environmental conditions enable healthy eudaimonic behaviors like exercise (Barton & Pretty, 2010; Plante, Cage, Clements, & Stover, 2006; Townshend, 2014), social interaction (Baum & Davis, 1980; Case, 1981; Kweon et al., 1998; Lund, 2002; Williams, 2005), and engagement (Anderson, 2014), while others hinder or restrict such activities. Environmental factors can also affect the emotions people experience in different places (Bratman, Daily, Levy, & Gross, 2015; Evans, 2003; K. Korpela, Borodulin, Neuvonen, Paronen, & Tyrväinen, 2014) as well as their sense of comfort (Fanger, 1973; Nicol & Humphreys, 2002; Steemers, 2015), which may, in turn, affect behavioral choices (Ryan & Deci, 2001). The physical environment has even been shown to have short-term impacts on psychological resources like vitality, self-esteem, and cognitive functioning (Bratman, Daily, et al., 2015; Pretty, Peacock, Sellens, & Griffin, 2005; Ryan et al., 2010). In short, many studies, including several robust longitudinal experiments (Baum & Davis, 1980; Bratman, Daily, et al., 2015; Kweon et al., 1998; Ryan et al., 2010), suggest that the design of the built environment can directly and indirectly influence all three dimensions of flourishing.

In some contexts, such as schools, specific design variables have been consistently linked to wellbeing-related outcomes. For instance, acoustic design of classrooms appears to be an important factor that influences learning in children (Schneider, 2002). Acute exposure to classroom noise has been shown to impair speech recognition (Johnson, 2000; Wightman and Kistler, 2005), decrease children’s performance on complex listening tasks (Klatte et al., 2010; Valente et al., 2012), and interfere with memory encoding processes (Hygge, 2003). Furthermore, chronic exposure to noise during childhood has been found to interfere with reading ability (Evans & Maxwell, 1997; Haines et al., 2001; Maxwell & Evans, 2000) and to impair cognitive development more generally (Lercher et al., 2003). Architectural features that influence noise levels include insulation design and ventilation strategies. Use of

mechanical ventilation systems in schools, for example, may contribute significantly to classroom noise levels (Shield & Dockrell, 2004). However, in one study comparing learning outcomes in Danish schools, classrooms with mechanical ventilation systems were found to be associated with higher markers of academic achievement compared to classrooms with natural ventilation systems (Toftum et al., 2015). Additionally, some research suggests that lighting conditions can influence mood (Knez, 1995) and academic performance (Jago & Tanner, 1999; Earthman, 2004), although other studies have produced evidence that runs contrary to these claims (Veitch, 1997). The effects of classroom lighting on student learning may also vary by gender and other demographic factors of students (Knez, 2001; Knez & Kers, 2000). In terms of more generalizable findings, research suggests that increased use of daylight in classrooms may benefit student learning (Earthman, 2004), although excess natural light can also cause unwanted effects like glare if improperly designed (Barnitt, 2003; Karpen, 1993; Baker & Steemers, 2002).

Thermal comfort is another important factor related to occupant wellbeing in classrooms and other environments. In addition to being a viable measure of wellbeing in its own right (Steemers, 2015), thermal comfort may also predict other wellbeing-related outcomes such as student learning (Buckley et al., 2004; Earthman, 2004). In his early laboratory studies, Fanger (1973) argued that humans live most comfortably within a narrow temperature range. His work emphasized absolute temperature as the most important variable in determining thermal comfort. However, scholars have questioned the ecological validity of Fanger's early studies, which were conducted in a highly controlled and artificial setting (Nicol & Humphries, 2002; Wong & Khoo, 2003). More recently, compelling evidence has emerged to support the notion of *adaptive comfort theory*. This theory suggests that people can achieve comfort in a wide range of temperatures and conditions by naturally adapting their behaviors in response to variable local climates. In contrast to Fanger's approach, research on adaptive thermal design suggests that occupants' *expectations* about and *control* over their local climate may have a greater influence on thermal comfort than absolute temperature (Baker & Standeven, 1995, 1996; de Dear & Brager, 1998; Nicol & Humphries, 2002). The historical progression of the literature on thermal comfort highlights some of the limitations of isolated variables and the benefits of using more holistic principles of environmental measurement, as discussed further in the next section of this chapter ("Quantities of parts vs. qualities of wholes").



Although some consistent evidence has emerged showing the effects of isolated environmental variables on specific wellbeing outcomes in certain contexts, the findings from the field as a whole are less clear. Researchers have struggled to propose generalizable design solutions from the results of this literature. “It is not at all straightforward how communities should be planned to allow for... health and wellbeing of people and society,” write Kyttä and Broberg. “The recent literature concerning the health-promoting qualities of urban structure reveals rather confusing results ”(Kyttä & Broberg, 2014, p. 628). Many of these studies consider the effects of isolated environmental parameters on specific health outcomes for specific types of users, so it is challenging to translate fragmented bits of evidence into integrated design solutions that must support all-around wellbeing for many types of occupants (Cooper & Burton, 2014).

Furthermore, comparing many of the studies from the broader literature on environmental wellbeing reveals an inconsistent and sometimes contradictory pool of evidence. For instance, some studies indicate that open-plan workplaces increase interaction and communication between employees (Chaboki et al., 2012; Hua, 2007; Hwang & Kim, 2012; Rashid et al., 2009; Rasila & Rothe, 2012) while others demonstrate negative effects of open-plan offices on attention, concentration, and productivity due to increased noise and distraction (Brennan et al., 2002; Kim & de Dear, 2013; Roelofsen, 2008; Smith-Jackson & Klein, 2009).<sup>4</sup> Thus, open-plan offices may benefit some aspects of wellbeing (e.g., increased social engagement) while inhibiting others (e.g., decreased autonomy over one’s surroundings). Residential proximity to urban green spaces has been paradoxically linked to both improved wellbeing (Hartig, 2008) and poor health (Ellaway, 2014). Factors thought to increase neighborhood walkability and exercise, like street connectivity, have been significantly correlated with both higher and lower physiological health measures such as

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<sup>4</sup> Some of the discrepancies in the findings of this research may be due to differences in how the terms “open-plan” vs. “closed-plan” offices are operationalized in study design (Sailer & Penn, 2009). One commonly-used type of interpretation defines open-plan offices as “office spaces with high concentration levels of work areas, subdivided, or not, by screens and filing cabinets,” and closed-plan offices as “conventional individual compartmentalized offices separated from each other [by permanent walls or windows]” (Roelofson, 2008, p. 203). However, these terms can be interpreted in a variety of ways, which is an important shortcoming of this area of research. While conflicting evidence exists even among studies that operationalize these terms in the same way (Sailer & Penn, 2009), employees working in traditional, closed-plan offices nonetheless tend to have higher satisfaction with their workplace than those working in open-plan offices (Birnholtz et al., 2007; Duval et al., 2002), indicating that overall, the detriments of open-plan workplaces may outweigh the drawbacks (Kim & de Dear, 2013).

weight and body mass (Robertson-Wilson & Giles-Corti, 2009). The study of neighborhood residential density reveals perhaps the most erratic results (Figure 1.5). Some studies have correlated high-density residential design with increased walking, more frequent social interaction, and a greater sense of community (Amole, 2009; Boyko & Cooper, 2014; Kyttä, Kahila, & Broberg, 2011; Moore, 1990; Silburn, Zubrick, De Maio, & Shepherd, 2006), while others have found that density fosters perceived crowding, social withdrawal, anxiety, and depression (Evans, 2003; Lehtinen, Michalak, Wilkinson, & Dowrick, 2003; Nadler, Bar-Tal, & Drukman, 1982; Ross & Jang, 2000; Walters et al., 2004; Wilcox & Holahan, 1976). The inconsistencies of these findings further explain why wellbeing research has had a limited impact so far on architectural design and urban planning.



**Figure 1.5: (L) "Healthy" high-density urban neighborhood (Cushman, 1941). (R) "Unhealthy" high-density urban neighborhood (D'Amato, 2011). The purpose of this comparison is to illustrate the idea that the holistic quality of an environment often cannot be measured by quantifying single variables such as density.**

Although many robust studies indicate that the environment influences wellbeing, rather confusing empirical relationships have emerged from this body of literature. One group of researchers remarked that the current state of understanding in this field “puts us in the position of early 19<sup>th</sup> century physicians, with their limited and erroneous notions about the transmission of disease before the science of epidemiology had been firmly established” (CABE, 2005, p. 2).

## Quantities of parts vs. qualities of wholes

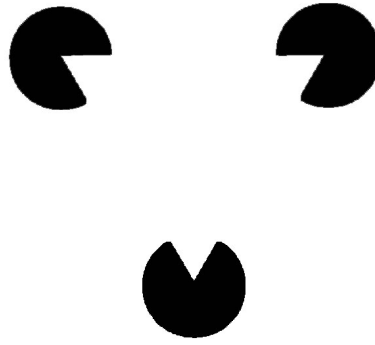
*“People experience urban spaces holistically... it is not easy to separate the [environmental] factors that influence their overall sense of wellbeing in such a way as to identify causality” (Adams, 2014, p. 264).*

Environmental wellbeing researchers have suggested that the biggest challenge in this field may be finding reliable metrics for evaluating aesthetic qualities of the built environment (Cooper & Burton, 2014). Most studies up to this point have investigated wellbeing outcomes in response to individual environmental parameters like residential density, building height, street connectivity, the length of city blocks, the length of building corridors, distance from public transportation, and so on. This approach is evident in existing environmental measurement tools like the Neighbourhood Design Characteristics Checklist, which attempts to evaluate residential environments by aggregating measurements of many individual design features thought to influence wellbeing (Burton, Mitchell, & Stride, 2011). This strategy adopts a mechanistic philosophy, in which the overall impact of a given environment on wellbeing is assumed to equal the sum of the independent health effects of each environmental parameter. In this model, each input parameter is thought to act in isolation, such that a given environmental variable like population density would have an independent and consistent impact on health, regardless of whatever other input parameters, like block length or street connectivity, might also be present in the given environment.

This strategy can approximate simple mechanical interactions, but it provides an inaccurate description of how systems behave. All parts of systems are interdependent, and the relative effect of each part on the behavior of the overall system changes depending on the arrangement of other parts surrounding it. In other words, the behavior of the whole system is “other than” the sum of the behavior of each component parameter (Koffka, 1935). This idea is illustrated below in the subjective contour diagram in Figure 1.6, which is a very simple system. Alone, each of the three black shapes resembles a Pacman-like figure. Only when the system is perceived as a whole does the white triangle in the middle emerge. The triangle is thus an *emergent property*, or *quality*, of the system that arises from the particular arrangement of all three components viewed together.<sup>5</sup>

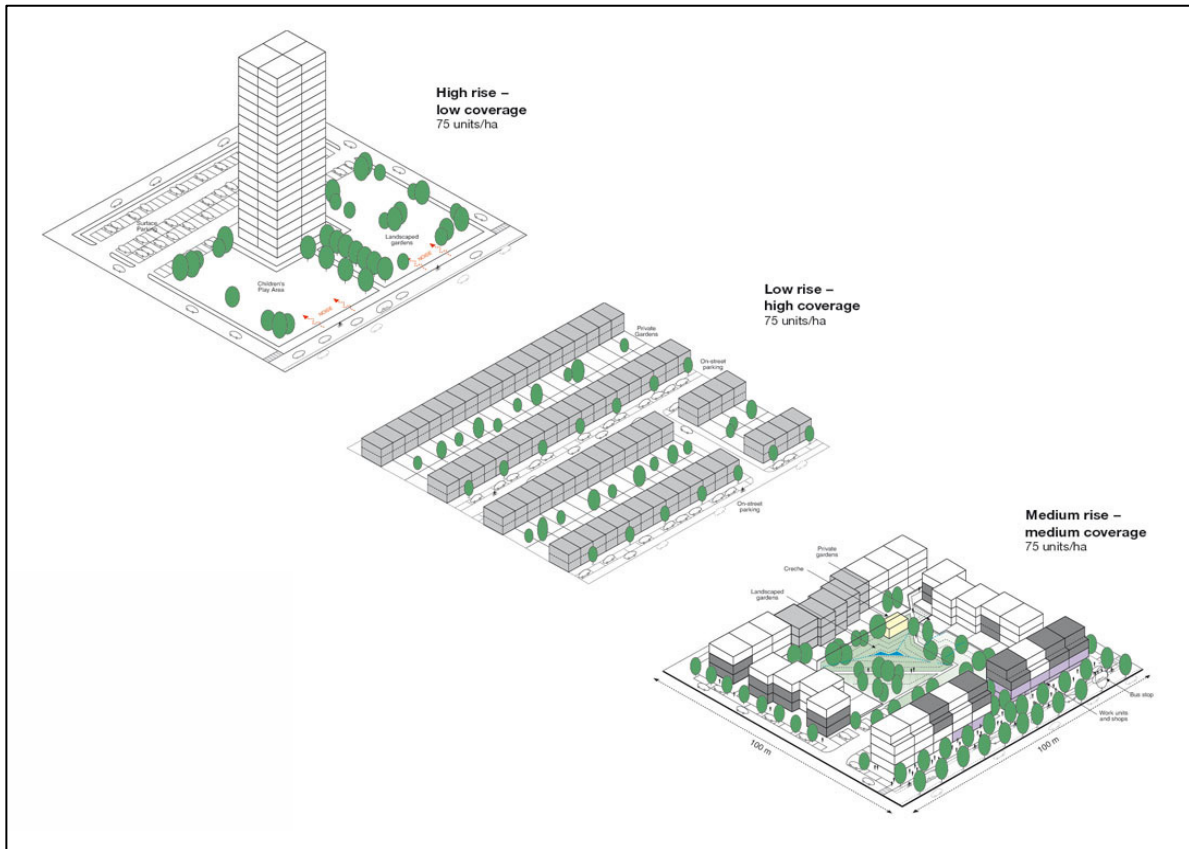
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<sup>5</sup> See Koffka (1935), *Principles of Gestalt Psychology*.



**Figure 1.6: The white triangle only emerges from the precise organization of the three black shapes (Dewey, 2007).**

This principle of interdependence also applies to more complex systems like the built environment. When people interact with a given environment, they perceive and respond to *qualities* of the whole system created by the organization of many interdependent parts (Adams, 2014; R. Kaplan & Kaplan, 1989). Each of these parts has a different effect on the overall system depending on the arrangement of other parts around it. For instance, a given density value in a neighborhood could be achieved alongside infinite possible arrangements of form, from single tower blocks to terraced low-rise row housing (Figure 1.7). “Whether or not the development promotes wellbeing is likely to depend more on these forms and... qualities than on overall density levels,” write Burton and Cooper (Cooper & Burton, 2014, p. 666). The interdependence of environmental parameters suggests that reductive individual metrics like density and building height may not provide much information about the actual environmental qualities people perceive.



**Figure 1.7: A given density value, which can be achieved by many different arrangements of form, reveals little about “quality” (Lord Rogers, 1999).**

An alternative strategy for environmental measurement is to evaluate the organization of all parts within a given environment and to identify the emergent qualities (or “white triangles”) that arise from the geometric order of the whole system. This method draws from the philosophy of systems thinking, a scientific approach that seeks to understand the interrelationships and interactions among all parts of a system rather than the quantities and mechanistic behaviors of a few isolated pieces.<sup>6</sup>

Several scholars have emphasized the importance of moving away from fragmented measures of the built environment and developing a more holistic understanding of environmental quality. Kyttä and Broberg write that “the currently dominating theoretical approaches... that focus on a limited number of individual measures should give way to ecological models; that is, the analysis of complex, situational processes at different scales of

<sup>6</sup> For more information on systems thinking, see Bohm (2002) *Wholeness and the Implicate Order* and Alexander (2011), “Systems generating systems.”

the environment” (Kytä & Broberg, 2014, p. 633). Cooper and Burton have similarly urged future researchers “to investigate the qualitative as well as the quantitative aspects of the built environment” and “to develop robust, quantitative ways of measuring the design qualities that matter, at the human scale” (Cooper & Burton, 2014, p. 666).

Evidence suggests, in fact, that aesthetic qualities of the built environment may predict wellbeing better than any single design variable measured in isolation (Adams, 2014; S. C. Brown, 2014; Ellaway, 2014; Kytä et al., 2011). Environments that are perceived as “attractive” and “high-quality,” for example, have been consistently linked to positive mental health outcomes (Carp, 1975; Ellaway, Macintyre, & Bonnefoy, 2005; Evans, 2003; Kytä et al., 2011; Obasanjo, 1999). In one cross-sectional study of residents ( $n = 1542$ ) of four towns in rural Finland, Kytä et al. (2011) found that perceived quality of the physical environment was significantly associated with self-reported quality of life ( $p < 0.01$  for 4/4 towns), health ( $p < 0.01$  for 2/4 towns), and well-being ( $p < 0.01$  for 1/1 towns). In a qualitative study of residential wellbeing in a major city in southwest England, residents were asked to describe qualities of their neighborhood surroundings that contributed to their wellbeing. 10 out of 36 categories of self-reported environmental features were specifically aesthetic features that residents said supported their ability to flourish. Examples of such aesthetic features of the neighborhood included “attractive houses/pleasing architecture,” “beautiful street,” “good/interesting view from the house,” and “attractive gardens” (Coles, 2014). In a large-scale study of adults ( $n = 3119$ ) in Helsinki and Espoo, Finland, Kytä and Broberg (2014) found that while no significant associations were found between quantifiable urban structural factors and wellbeing, the overall, perceived environmental quality was nonetheless highly and positively associated with perceived happiness, health, and quality of life.

Additionally, much has been written about the beneficial effects of nature on wellbeing (Berman et al., 2012, 2008; Berto, 2005; Bratman, Daily, et al., 2015; Bratman, Hamilton, & Daily, 2012; Bratman, Hamilton, Hahn, Daily, & Gross, 2015; S. Kaplan, 1995; see chapters 4 and 5 for an in-depth review of this extensive body of literature). Research suggests that aesthetic features of nature may play an important role in driving these salubrious effects. In one laboratory study, for instance, participants who were exposed to more beautiful images of nature exhibited significantly more generous and trusting behaviors than those who were exposed to less beautiful images of nature. Likewise, participants exposed to more beautiful

images of nature demonstrated a higher incidence of helping behaviors than a control group (Zhang et al., 2014). Beautiful urban environments have also been shown to induce restorative effects. In one study of college students who were stressed by the act of taking an exam ( $n = 86$ ), exposure to videos of “attractive” urban environments (as rated by participants) were shown to have a stress-reducing and mood-enhancing effect similar to that of an attractive natural environment (Karmanov & Hamel, 2008). A number of studies suggest that low-level aesthetic features may mediate the effects of natural environments on wellbeing (Berman et al., 2014; Kardan et al., 2015; Kotabe et al., 2016; Kotabe et al., 2017; Ibarra et al., 2017; see also Chapter 5 for further discussion of this topic).

Collectively, these studies suggest that aesthetic qualities of physical environments, including perceived beauty and naturalness, may play an important role in determining whether or not an environment will enable its occupants to flourish. “Attractiveness is a key element in how the built environment affects our wellbeing,” write Cooper and Burton. “Numerous studies show that people who live in more attractive environments...are better off” (Cooper & Burton, 2014, p. 665). Few researchers, however, have proposed concrete definitions of environmental quality or beauty that provide practical design guidance for architects and planners. “We know that we should design and deliver attractive environments,” Cooper and Burton continue. “But we don’t know what these are. It is perhaps the holy grail of architecture: to understand what constitutes beauty” (Cooper & Burton, 2014, p. 665).

This gap in the empirical literature has motivated the present research, which aims to advance our understanding of how aesthetic qualities of the built environment influence psychological experiences and wellbeing. Two major challenges face this line of research, which can be summarized as “measuring the environment” and “measuring environmental perception.” These two challenges are addressed below.

## **Evaluating aesthetic responses to architecture**

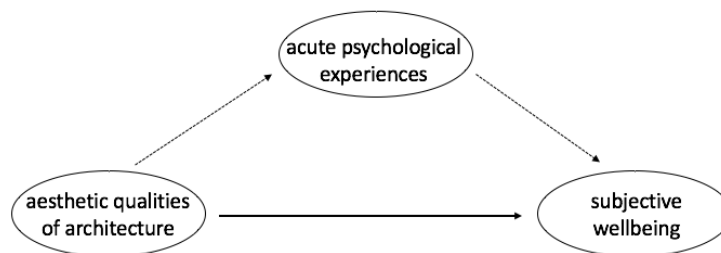
### *Measuring the environment*

Previous studies in environmental wellbeing have generally relied on simple and easily quantifiable measures of the built environment such as building height, corridor length, and occupant density. However, these reductive variables often fail to capture the complex sensory qualities of buildings and urban spaces. Chapters 4 and 5 of this dissertation introduce

more comprehensive environmental measures, like pattern theory (Alexander, 2002) and image statistics (Berman et al., 2014; Kardan, Demiralp, et al., 2015), that can be used to evaluate aesthetic qualities of architectural design. Chapter 4, discusses the link between environmental *naturalness* and wellbeing and introduce Christopher Alexander's theory of natural structure (Alexander, 2002), which proposes a series of nature-like patterns in architecture that have been theoretically linked to human flourishing. In Chapter 5, psychological responses are measured to two of Alexander's proposed patterns of natural structure, which are quantified in two sets of architectural scenes using image statistics. These studies pave the way for future researchers to operationalize complex aesthetic features of the built environment and to investigate how such features influence psychological experiences, behavior, and wellbeing.

### *Measuring environmental perception*

A second challenge involves measuring acute psychological responses relevant to design. The impact of architecture on wellbeing is likely mediated by the nervous system, via acute perceptions and psychological experiences such as cognitive and emotional responses to design (Figure 1.8). Researchers have often examined how design features impact long-term mental health measures such as depression and life satisfaction. Fewer studies, however, have investigated short-term aesthetic responses to the built environment. These acute psychological experiences may have a magnified impact on longer-term behaviors and mental states when an environment is experienced habitually or for prolonged periods of time, as is often the case with home, school, and office environments.



**Figure 1.8: Acute psychological responses to architecture may mediate the influence of design on wellbeing (figure designed by the author).**

The past few years have witnessed a burgeoning interest in the psychology and neuroscience of architecture (Coburn, Vartanian, & Chatterjee, 2017; L. T. Graham, Gosling, & Travis, 2015; Joye & Dewitte, 2016; Vartanian et al., 2013, 2015; Vecchiato et al., 2015). Researchers have



tested a wide variety of neural and psychological responses to architectural design features, including perceptions of beauty (Vartanian et al., 2013), feelings of awe (Joye & Dewitte, 2016), and approach-avoidance decisions (Vartanian et al., 2015), as well as neurophysiological measures of stress (Fich et al., 2014), pleasure (Vartanian et al., 2013), and visuospatial exploration (Vartanian et al., 2015; Vecchiato et al., 2015). However, the disparate dependent variables tested in these studies remain disconnected from any cohesive theoretical framework.

The first two chapters of this thesis offer new frameworks to contextualize measures of neural and psychological responses to the built environment. Chapter 2 outlines the first neuroscientific model of architectural experience by proposing that aesthetic responses to architecture arise from integrated activity in sensorimotor, emotion-valuation, and knowledge-meaning systems of the brain. In Chapter 3, a principal components analysis (PCA) is conducted on a series of psychological variables measured in response to interior architectural scenes. Through this analysis, three primary dimensions of psychological experience are identified in response to the architectural scenes: *fluency*, *fascination*, and *hygge*. Outlining the complex neural and psychological processes underpinning architectural encounters represents an important step towards understanding how aesthetic features of architecture influence our short-term mental states and, over time, contribute to our overall sense of wellbeing.

### **Conclusion**

Buildings surround us most of the time, and evidence suggests that architectural design can have a meaningful impact on our ability to flourish. However, past research linking isolated features of the built environment to long-term wellbeing outcomes has yielded rather confusing results. The following chapters of this dissertation aim to address the important gaps in knowledge highlighted here by investigating how aesthetic qualities of architectural spaces influence short-term perceptions and psychological experiences. Through prolonged or repeated exposure, these acute aesthetic responses to architectural spaces may influence longer-term hedonic measures like mood and happiness, as well as eudaimonic behaviors like exercise patterns and social interaction. The next chapter advances this research by investigating the neural underpinnings of aesthetic experiences in the built environment.

# Chapter 2:

## A neuroscientific model of architectural experience<sup>7</sup>

### Introduction

This chapter explores how neuroscience can help elucidate the anatomical underpinnings of aesthetic experiences in the built environment. A burgeoning interest in the intersection of neuroscience and architecture promises to offer biologically inspired insights into the design of spaces. The goal of this interdisciplinary research is to motivate construction of environments that would contribute to peoples' flourishing in behavior, health, and wellbeing. This nascent field of neuroarchitecture is at a pivotal point in which neuroscience and architecture is poised to extend to a neuroscience of architecture. In such a research program, architectural experiences themselves are the target of neuroscientific inquiry. This chapter draws lessons from recent developments in neuroaesthetics to suggest how neuroarchitecture might mature into an experimental science. An initial neural framework is proposed to contextualize previous research. The chapter concludes by outlining the theoretical and technical challenges that lie ahead.

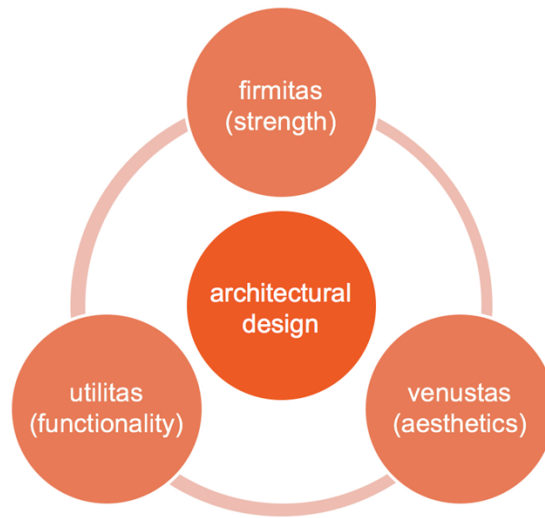
### Beauty and architectural experience

Two thousand years ago, the Roman architect Vitruvius highlighted *beauty* as one of three core dimensions of architectural design. His seminal *Vitruvian triad* (Figure 2.1) illustrated that a building must be strong and structurally stable (*firmitas*), meet the functional needs of its occupants (*utilitas*), and appeal to their aesthetic sensibilities (*venustas*) (Vitruvius Pollio, Morgan, & Warren, 1914). For millennia, non-western cultures across the globe have also regarded aesthetic experience as a vital consideration in human construction. Ancient Eastern construction practices like the Indian vastu shastra and the Chinese feng shui offered concrete guides to creating spatial harmony and aesthetic coherence in the built environment (Mak & Thomas Ng, 2005; Patra, 2009). Architectural aesthetics was a topic of serious inquiry in the European intellectual tradition as well, generating attention from philosophers like Goethe and Ruskin (Hultzs, 2014). The considerable attention devoted to this subject across

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<sup>7</sup> A previous version of this chapter was published in the *Journal of Cognitive Neuroscience* with the title "Buildings, beauty, and the brain: a neuroscience of architectural experience" (Coburn, Vartanian, & Chatterjee, 2017).

time and culture reflects a shared belief that aesthetic qualities of buildings have a meaningful impact on human experience.



**Figure 2.1: The Vitruvian triad (this figure was designed by the author and was published in Coburn et al., 2017).**

In the 20<sup>th</sup> century, the aesthetic dimension of the built environment was somewhat deemphasized relative to the other Vitruvian dimensions (Alexander, 2002; Salingaros, 2007; Venturi, Scott Brown, Rattenbury, & Hardingham, 2007). Modern building science generally focused on improving utilitarian measures like fire safety, construction costs, and efficient uses of space (Vaughan, 2013). Advances in material design and structural engineering led to the construction of taller and sturdier buildings than ever before (Ali & Moon, 2007). This trend mirrored a philosophical shift in Western architectural practice that began about a century ago, when the concept of buildings as machines and the associated creed of “form follows function” influenced architects to optimize the measurable and often mechanistic aspects of the built environment while discarding long-observed aesthetic conventions like ornamentation and human scaling. The minimalist, reductive form that resulted from this philosophy came to embody a new aesthetic ideal, reflecting a view of architectural beauty as nothing more than a byproduct of functionalist design (Venturi et al., 2007). This perspective pushed the study of aesthetic experience to the periphery of architectural investigation. In Vitruvian terms, *venustas* was subsumed by *utilitas*.

Recent decades, however, have witnessed a surge of interest in the experience of the built environment. Today, many people spend upwards of 90% of their lives in buildings (Evans & McCoy, 1998). Studies indicate that aesthetic qualities of architecture have an impact on our

mood, cognitive functioning, behavior, and mental health (Adams, 2014; Hartig, 2008; Huppert & Cooper, 2014; Joye, 2007b). This evidence coincides with a flourish of interest in the intersection of neuroscience *and* architecture (Dance, 2017; Eberhard, 2008; Mallgrave, 2010a; Robinson & Pallasmaa, 2015). However, relatively little empirical work has been conducted on the neuroscience *of* architecture. Future research must go beyond inferences from neuroscientific knowledge applied to architecture to direct experimental work in which architectural experience itself is the target of neuroscientific research.

### **Lessons from neuroaesthetics**

Here, lessons are applied from recent developments in neuroaesthetics, a discipline that investigates the neurobiological underpinnings of aesthetic experiences of beauty and art (Chatterjee & Vartanian, 2016), to the neuroscience of architecture. These ideas and methods can be used to study aesthetic experiences in the built environment (Eberhard, 2009). An emerging “neuroscience of architecture” promises an empirical platform from which to study the experiential dimensions of architecture that have been largely overlooked in modern building science.

Around 2004, neuroaesthetics arrived at a pivotal point in its development both empirically and theoretically. The first papers using functional magnetic resonance imaging (fMRI)<sup>8</sup> to identify neural responses to art (Vartanian & Goel, 2004) and to critically review the neuropsychology of art (Chatterjee, 2004b, 2004a) were published. In concert and perhaps more importantly early models outlining key cognitive and neural systems involved in aesthetic experience were set forth (Chatterjee & Vartanian, 2014; Leder, Oeberst, Augustin, & Belke, 2004). Previous research had been primarily *descriptive* in that most studies generated qualitative observational claims relating facts of the brain to aesthetic experiences (Chatterjee & Vartanian, 2014). The pivot initiated a shift from descriptive hypothesis-generating research to empirical hypothesis-testing studies and helped launch the discipline into the mainstream of scientific investigation (Chatterjee, 2011).

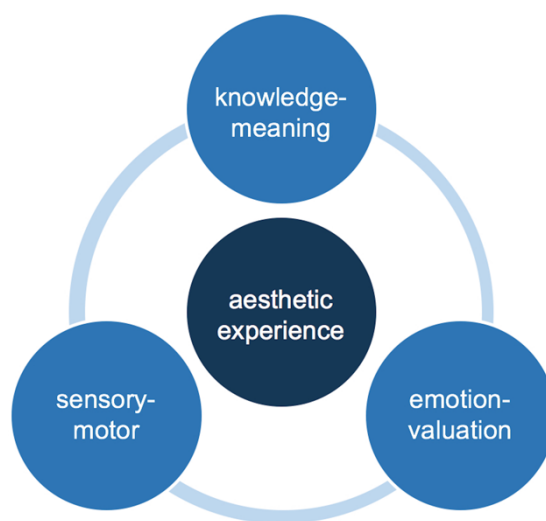
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<sup>8</sup> fMRI is a technology that measures neural activity by monitoring changes in blood flow to different areas of the brain. Since neuronal activation and blood flow are coupled, increased blood flow to a certain brain region implies greater neural activity in that region.

The neuroscience of architecture is on the verge of a similar pivot. Currently, descriptive research predominates in this young field (M. G. Brown & Lee, 2016; Eberhard, 2008; Mallgrave, 2010b). Several empirical studies have recently emerged reporting neurophysiological responses to architectural parameters (Choo, Nasar, Nikrahei, & Walther, 2017; Marchette, Vass, Ryan, & Epstein, 2015; Shemesh et al., 2017; Vartanian et al., 2013, 2015). These studies represent a first step. However, they remain untethered to a general theoretical framework and are difficult to place in the context of programmatic research on the neuroscience of architecture. Below, a general neural model of aesthetic experience is applied to architectural experience in order to contextualize past and future empirical studies.

### **The aesthetic triad: a neural model of architectural experience**

The *aesthetic triad*, originally created to frame aesthetic experiences in neural terms (Chatterjee, 2013; Shimamura, 2013), also applies in a general way to the neuroscience of architecture. According to this model, three large-scale brain systems generate aesthetic experiences: sensorimotor, knowledge-meaning, and emotion-valuation systems. Architecture engages multiple sensory networks, presumably visual, auditory, somatosensory, olfactory and vestibular systems, and triggers motor responses such as approach and avoidance (Vartanian et al., 2015). Meaning-knowledge systems informed by personal experiences, culture, and education also shape one's encounters with the built environment. Finally, emotion-valuation networks mediate feelings and emotions engendered by buildings and urban spaces (Leder et al., 2004).



**Figure 2.2: The Aesthetic Triad (Chatterjee & Vartanian, 2014)**

Each of these systems is discussed in greater detail below, and the relative contribution of each system to emergent aesthetic experiences of architecture is considered. There is also discussion of how these networks might respond differently to architecture than to visual art. Key differences include the immersive and multisensory nature of buildings and the prolonged time span of architectural encounters as compared to typically two-dimensional images and brief engagement with artworks. Along the way, this review considers how aesthetic experiences could mediate the effects of architecture on behavior, health and wellbeing, and how differences in building types (e.g., homes, hospitals, office space, museums) might modulate the nature of these experiences.

A general question that arises in neuroaesthetics is whether art objects are special and whether aesthetic experiences of art are different than aesthetic experiences of natural or non-art objects. A similar question could be raised for architecture. There are similarities and differences in people's responses to built versus natural environments. There are likely systematic differences in the sensory properties (color, texture, shapes) of built and natural spaces and that architectural knowledge or familiarity of these spaces are likely to introduce differences in their respective experience. Understanding these similarities and differences is also of scientific interest.

### **Sensory-motor systems**

Edmund Burke remarked that "beauty is, for the greater part, some quality in bodies acting mechanically upon the human mind by intervention of the senses" (Burke, 1767, p. 175). Indeed, sensory networks can be considered the gatekeepers of architectural experience. Environmental features differentially stimulate our visual, auditory, somatosensory, vestibular and olfactory neural networks. These sensations are tied to downstream motor responses such as the affordances of objects, approach and avoidance reactions, and navigation through built spaces.

#### *Vision*

Vision dominates research in perception of architectural spaces. Basic low-level visual attributes such as luminance, color, and motion, and intermediate levels like grouping, are processed (Chatterjee, 2004a) before integration into higher-level processing areas such as the parahippocampal place area (PPA), the retrosplenial cortex (RSC) and the occipital place

area (OPA) (Marchette et al., 2015). The PPA responds specifically to environmental scenes, including landscapes, building interiors, and urban neighborhoods, and also plays a critical role in spatial navigation (Epstein & Kanwisher, 1998; Mégevand et al., 2014). This area also codes for the expansiveness of spaces (Kravitz, Peng, & Baker, 2011). Recent work suggests that the OPA is involved in processing perceptual features like building materials, windows and architectural motifs that might be relevant to recognizing the interior and exterior of buildings. By contrast, the RSC retrieves information that allows people to orient themselves within a remembered or imagined spatial environment (Marchette et al., 2015). Hippocampal and entorhinal cortices contribute to different aspects of spatial navigation, which would be relevant for architectural experiences (Spiers & Barry, 2015).

A prominent idea in visual aesthetics is the notion of fluency (Reber, Schwarz, & Winkielman, 2004). That is, by hypothesis, humans prefer configurations with some degree of complexity that are also processed easily or fluently. The visual system is sensitive to features like contrast, grouping, and symmetry (Ramachandran & Hirstein, 1999). Retinal cells and neurons in the occipital cortex are more responsive to edges, or areas of high visual contrast, than to regions of homogenous luminance in a scene (Brady & Field, 2000; Geisler, 2007; Ramachandran & Hirstein, 1999). High-contrast regions often capture visual attention and interest because they contain a high density of useful visual information for object identification (Alexander, 2002; Hagerhall, Purcell, & Taylor, 2004; Leder et al., 2004; Ramachandran & Hirstein, 1999). Grouping, a fundamental Gestalt principle, describes the process by which the visual system orders repeated, statistically-correlated information in a scene, like alternating columns and archways in an architectural colonnade or organized patterns of blue and yellow hues dispersed throughout a stained glass window (Alexander, 2002). Grouped features (e.g., of color or form) trigger synchronized action potentials among associated neurons responsible for processing those features (Ramachandran & Hirstein, 1999; Singer & Gray, 1995). These visual mechanisms may mediate the pleasure response associated with viewing ordered patterns of form and color in architecture (Alexander, 2002).

Balance, of which symmetry is the most straightforward example, also contributes to fluency and aesthetic preference (A. Wilson & Chatterjee, 2005). The evolutionary importance of symmetrical information as a reproductive fitness indicator for human survival may underlie experimentally observed preferences for more symmetrical faces and geometric shapes (Frith

& Nias, 1974; Jacobsen, Schubotz, Höfel, & Cramon, 2006; Ramachandran & Hirstein, 1999; Rhodes, Proffitt, Grady, & Sumich, 1998). Alexander and Carey reported that the number of local symmetries in a given pattern strongly predicts the ease with which a participant can find, describe, and remember that pattern (Alexander & Carey, 1968). Patterns with more symmetries enable more efficient recognition. The fundamental importance of symmetry may help explain why this pattern appears ubiquitously in human design and construction at many scales, from Persian rugs to Shaker furniture to ancient Greek temples (Alexander, 2002).

The visual system is sensitive to various statistical properties of images. One such property is fractal geometry, defined as “fractured shapes [that] possess repeating patterns when viewed at increasingly fine magnifications” (Hagerhall et al., 2004, p. 247). Fractal geometry provides a mathematical description of mountains, coastlines, and many other complex shapes in nature (Hagerhall et al., 2004). A fractal dimension is a statistical index of complexity. For example, a simple curve has a fractal dimension close to 1, whereas a densely convoluted line that approximates the appearance of a surface has a fractal dimension closer to 2. Aesthetic preferences for natural scenes, visual art, and computer-generated patterns seem to correlate moderately with fractal dimensions ranging from about 1.3 to 1.5 (Spehar, Clifford, Newell, & Taylor, 2003; Taylor et al., 2005), although these claims remain deeply controversial (Jones-Smith & Mathur, 2006). In general, quantifiable image statistics do contribute to the psychophysics of aesthetic responses (Berman et al., 2014; D. J. Graham & Field, 2007; D. J. Graham & Redies, 2010; D. J. Graham, Schwarz, Chatterjee, & Leder, 2016; Kotabe, Kardan, & Berman, 2016b; Redies, 2007), which would also apply to built environments.

Beyond formal mathematical definitions, colloquial notions of complexity, defined as “the volume of information present in a space” (Dosen & Ostwald, 2016, p. 3), may influence the ease with which we identify objects and extract information from the built environment. Salingaros suggested that buildings stripped of visual complexity, like prisons, deny the information-seeking visual system access to meaningful information (Salingaros, 2003). Empirical findings tentatively support this view, suggesting that people generally prefer at least a moderate level of visual complexity when viewing both art and architectural interiors (Dosen & Ostwald, 2016; Frith & Nias, 1974; Leder et al., 2004). As Berlyne postulated many years ago, preferences tend to follow an inverted U-shaped curve in relation to complexity



(Daniel E. Berlyne, 1970, 1971; Güçlütürk, Jacobs, & van Lier, 2016; Ç. Imamoglu, 2000). More recent evidence suggests that the relationship between complexity and aesthetic preference varies as a function of how the former is conceptualized (e.g., amount, variety or organization of elements within a scene) (Nadal, Munar, Marty, & Cela-Conde, 2010). Excess architectural complexity may also overwhelm the visual system, particularly if the information is experienced as disorganized (Kotabe et al., 2016b; Salingaros, 2003, 2007).

Appleton's *habitat theory* offers an evolutionary framework to explain psychological responses to architectural spaces. According to habitat theory, humans evolved to prefer landscapes containing visual features and spatial configurations that favor survival (Appleton, 1975). People may have an innate visual preference for moderately complex, savannah-like environments (Balling & Falk, 1982; Joye, 2007b), because these areas signal both safety and nourishment. The frequent patches of trees scattered throughout the savannah (Joye, 2007b) likely offered early hominids places to hide from predators and survey the plains in search of resources, mates, and prey (Appleton, 1975). A review by Dosen and Ostwald indicates that both prospect (a clear view of the environment) and refuge (safe places to hide) predict visual preferences for natural settings and that these preferences also extend to built environments (Dosen & Ostwald, 2016). People often prefer architectural interiors and urban spaces that are more open and visually connected to their surroundings compared to enclosed environments (Dosen & Ostwald, 2016). An fMRI study of architectural interiors found that participants judged open rooms as more beautiful than enclosed rooms (Vartanian et al., 2015). Open interiors activated structures in the temporal lobes associated with perceived visual motion, including the left middle temporal gyrus and the right superior temporal gyrus (Vartanian et al., 2015). Subjects in this study also preferred rooms with higher ceilings over those with lower ceilings, which could be interpreted as a preference for greater visual prospect. Supporting this interpretation, high ceilings activated structures associated with visuospatial attention and exploration, including the left precuneus and the left middle frontal gyrus (Vartanian et al., 2015).

E.O. Wilson's *biophilia hypothesis* proposes that our sensory systems developed heightened sensitivity to living and life-like stimuli of the natural world (E. O. Wilson, 1984). Kaplan and colleagues proposed that inherently fascinating visual stimuli in natural landscapes, like vegetation, wildlife, and "the motion of leaves in the breeze" (S. Kaplan, 1995, p. 174), capture

the attention of our visual system in a bottom-up fashion (Berman et al., 2014; Berman, Jonides, & Kaplan, 2008; Ulrich & Parsons, 1992). This body of work suggests that humans are more likely to orient and attend to these “soft fascinations” (S. Kaplan, 1995, p. 174) associated with living and natural objects.

Biomorphic features are also prevalent in human construction. Builders throughout history have often endowed their structures with nature-like visual qualities by drawing inspiration from the “monumental design model” (Kellert, 2003, p. 36) of plants and animals in the design of ornamentation, scaling, proportionality, and even structural support schemes (Alexander, 2002; Joye, 2007b). Several authors have speculated about the potential sensory and emotional benefits of naturalistic patterns in architecture, like curvilinear form and fractal scaling (Alexander, 2002; Joye, 2007b; Salingaros, 2007). For instance, Vartanian and colleagues found that images of curvilinear architectural interiors activated the lingual and the calcarine gyrus in the visual cortex more than images of rectilinear interiors when participants made approach-avoidance choices (Vartanian et al., 2013). Psychological responses to nature-like patterns are further explored in Chapter 5 of this dissertation.

### *Non-visual experiences of architecture*

Relatively little empirical research has been conducted on non-visual aspects of architectural experiences. Odor affects an occupant’s emotional response to a building (Barbara & Perliss, 2006), perhaps because of the direct link between the olfactory and limbic system (Ward, 2015). Olfaction can revive memories of past experiences in a place, like a childhood home, by activating neural structures governing memory, affect, and meaning (Lehrer, 2008).

Acoustics also play a key role in shaping an occupant’s experience. Audition helps provide inhabitants with useful information about the size and shape of an architectural space (Ward, 2015). Acoustic parameters like reverberation time affect the fullness and complexity of the sound perceived and probably contributes to whether a place is designed for contemplation as in a monastery or for excitement as in a stadium.

The somatosensory cortex mediates an occupant’s tactile and thermal sensations of buildings. A building’s temperature, for instance, influences an occupant’s comfort, emotional state, and perception of beauty (Fanger, 1973; Nicol & Humphreys, 2002; Thorsson, Honjo, Lindberg, Eliasson, & Lim, 2007). The tactile nature of materials used undoubtedly plays a role

in the experience of interior spaces, but this sensory quality has not received substantial experimental scrutiny.

### *Motor responses to architecture*

Navigating buildings involves planning and execution of movement, and it is likely that architectural design differentially impacts neural areas responsible for motor planning and navigation. Beauty evaluations of architecture can vary with neural activity in the global pallidus (Vartanian et al., 2013), perhaps suggestive of motor responses (Nambu, Tokuno, & Takada, 2002). Aesthetic parameters like enclosure has an impact on decisions to approach or avoid a space (Vartanian et al., 2015), which may be governed by reward and emotion processing areas like the nucleus accumbens, the anterior insula, and the basolateral amygdala (Vartanian et al., 2013). Intriguingly, Joye and Dewitte found that exposure to images of tall buildings – which were associated with heightened feelings of awe – caused participants to experience greater immobility and to respond more slowly on a manual clicking task than exposure to images of low buildings (Joye & Dewitte, 2016). These findings suggest that our aesthetic evaluations of architecture can propel or inhibit motor activity and influence the specific qualities of the viewers' experiences.

### **Knowledge-meaning systems**

Education, memories, and the context in which a person encounters an aesthetic object or a built environment can have an impact on the person's experience. Expertise, for instance, is known to influence aesthetic experiences. In one fMRI study, architecture students recruited different cortical areas when viewing buildings than students from other disciplines (Wiesmann & Ishai, 2011). Another experiment showed that architects, compared to non-architects, had increased activation of reward circuitry, including the bilateral medial orbitofrontal cortex and the subcallosal cingulate gyrus, when making aesthetic judgments about buildings (Kirk, Skov, Christensen, & Nygaard, 2009). Architects also exhibited greater activation of the hippocampus and precuneus compared to control participants when viewing buildings but not faces, suggesting that memories rendered by education and professional experience contributed to their affective responses.

These more recent fMRI studies build on a significant body of earlier psychological research revealing differences in aesthetic preferences between architects and non-architects

(Friedman, Balling, & Valadez, 1985; Gifford, Hine, Muller-Clemm, & Shaw, 2002; Nasar & Purcell, 1990). For instance, one study of aesthetic preferences for housing design (Devlin & Nasar, 1989) showed that non-architects preferred “popular” style residential architecture (characterized by use of more building materials, horizontal orientation, hip roofs, framed windows, centered entrances, and warm colors), whereas architects favored “high” style housing design (characterized by fewer materials, more concrete, simpler forms, more white, and off-center entrances). Another study found that architects tend to describe buildings using abstract and conceptual terminology, whereas non-architects are more likely to assess buildings using emotion-based descriptions (Devlin, 1990). In a cross-sectional study of aesthetic preferences of architectural students at two schools of architecture, Wilson (1996) found that students tend to evaluate buildings based on architectural style, supporting her hypothesis that preferences of architects are influenced by the process of socialization that typically occurs during architecture school. Evidence has also emerged to suggest that architects are poor predictors of non-architects’ architectural preferences, both for homes of varying styles (Nasar, 1988) and for large contemporary buildings (Brown & Gifford, 2001). To explain these discrepancies, research suggests that architects and non-architects may use different categorization schemes (Gifford, Hine, Muller-Clemm, & Shaw, 2002; Groat, 1982) and different interpretive categories (Devlin, 1990) when evaluating buildings. In combination with later fMRI research (Kirk, Skov, Christensen, & Nygaard, 2009; Wiesmann & Ishai, 2011), this research suggests that architectural training may alter important cognitive processes that people use to evaluate buildings, thus resulting in differences in both aesthetic preferences and neural responses between architects and non-architects.

A person’s past experiences in a built environment can modulate their present interactions with that space. Exposure to an environment generates a cognitive map using place and grid cells of the hippocampus (McNaughton, Battaglia, Jensen, Moser, & Moser, 2006; O’Keefe & Nadel, 1978), which in turn facilitates more efficient navigation in future encounters (Astur, Taylor, Mamelak, Philpott, & Sutherland, 2002; Maguire et al., 2000). Grid cells encode memories of both events and the places in which they occur (Edelstein et al., 2008). Since familiarity influences liking (Montoya, Horton, Vevea, Citkowicz, & Lauber, 2017), it is likely that familiarity and ease of navigation would influence the aesthetic experience of spaces.

How might expectations, context, and meaning affect a person's architectural experience? Expectations about control influence thermal comfort. Occupants who control environmental parameters affecting building temperature, such as operable windows, fans, and thermostats, tolerate a wider range of indoor temperatures than inhabitants with restricted control over their indoor climate (Nicol & Humphreys, 2002). The mere perception of environmental control can increase the range of temperatures within which an occupant feels comfortable (Bauman et al., 1994; Brager et al., 2004). Context and cultural meaning also have an impact on aesthetic experience (Leder et al., 2004). Kirk and colleagues found that participants were more likely to judge abstract visual art as beautiful if they were labeled as gallery pieces than if they were classified as computer-generated images (Kirk, Skov, Hulme, Christensen, & Zeki, 2009). Art randomly assigned the "gallery" label generated increased activity in prefrontal, orbitofrontal, and entorhinal cortices than those assigned the "computer" label, indicating that participants' expectations about the aesthetic value of the artworks influenced their emotional responses.

Similar to the gallery condition for art, a building's advertised cultural significance could shape an occupant's expectations and alter his or her experience of the space. For example, this effect might bias people to enjoy and appreciate expensive buildings, buildings designed by famous architects, buildings perceived as sustainable, or buildings associated with a particular historical period, event, or style. Aesthetic appreciation of visual art can be influenced by the degree to which it appeals to social status and financial interest (Konecni, 1979; Ritterfeld, 2002), and similar phenomena may also apply to aesthetic appreciation of architecture. Knowledge of a structure's intended function could similarly bias an occupant's expectations before their architectural encounter. The prospect of visiting a prison, for example, would likely bring on a different frame of mind than the experience of preparing to enter a Buddhist temple. Thus, the knowledge and expectations that a person brings to the space they occupy almost certainly influences their aesthetic experience of that space. These expectations are likely shaped by personal, cultural and social factors. For instance, aesthetic judgements in general have been shown to be influenced by a person's socioeconomic and cultural background (Konecni, 1979; Jacobsen, 2002; Ritterfeld, 2002). It is reasonable to expect that such inter-individual differences would apply to perceptions of architecture as well (Graham et al., 2015; Ritterfeld, 2002).

### **Emotion-valuation systems**

The emotions people feel in the presence of beautiful architecture are likely mediated by the brain's reward circuitry. In a meta-analysis of neuroimaging studies investigating positive-valence aesthetic appraisal, Brown and colleagues proposed that the processing of aesthetic emotions occurs through a core neural circuit involving the orbitofrontal cortex (OFC), the basal ganglia, the anterior cingulate cortex (ACC), and the anterior insula (S. Brown, Gao, Tisdelle, Eickhoff, & Liotti, 2011). One study revealed that curvilinear building interiors are judged as more beautiful and pleasing than rectilinear spaces, and that beauty ratings of curved rooms correlated with increased activation of the anterior cingulate cortex (ACC), which is a region of the brain associated with emotional salience monitoring (Vartanian et al., 2013). The ACC is connected with both the orbitofrontal cortex (OFC), which processes emotion and reward in decision-making, and anterior insula, which is also involved in emotional processing. The ACC is often co-activated with these regions in neuroimaging studies of rewards (S. Brown et al., 2011).

A follow-up experiment found that participants' inclinations to exit enclosed rooms, compared to open rooms, were associated with activation of the anterior midcingulate cortex (aMCC) (Vartanian et al., 2015). The aMCC receives direct projections from the amygdala (Vogt & Pandya, 1987) and is involved in fear processing (Whalen et al., 1998), pointing out that brain circuitry governing negative emotions almost certainly play a role in architectural experience. Another group of researchers found that study participants immersed in a virtual simulation of an enclosed room without windows exhibited greater reactivity to a stress test than participants who undertook the test in a virtual room with windows (Fich et al., 2014). Those who took the test in the enclosed virtual space experienced both heightened and prolonged spikes in salivary cortisol compared to participants immersed in the more open environment. In these two studies, the same design parameter, enclosure, produced both fear and elevated levels of stress hormones, presumably because emotion-regulating limbic structures like the amygdala modulate downstream activity of the neuroendocrine and autonomic nervous systems (Ulrich-Lai & Herman, 2009). The close association between the limbic system and stress responses represents a key pathway by which chronic exposure to maladaptive built environments might negatively impact an occupant's long-term health (Joye, 2007b).

The idea that the visual and limbic systems work in concert to rapidly identify and evaluate incoming visual information is consistent with Ulrich's framework, which proposes that initial affective responses towards environments are primarily influenced by automatic, unconscious processing (Ulrich, 1983). Some studies suggest that positive and negative emotional responses to environmental scenes occur rapidly and automatically (Hietanen & Korpela, 2004; Joye & Dewitte, 2016; K. M. Korpela, Klemettilä, & Hietanen, 2002; Valtchanov & Ellard, 2015). Such a quick emotional response could be adaptive by relieving people of the cost imposed by learning an environment through actual lived experience (Joye, 2007b; S. Kaplan, 1987; Ulrich, 1983).

If there is indeed an evolutionary basis for aesthetic sensation and emotion, then architects could manipulate the design parameters of their buildings to heighten these adaptive responses. In fact, builders throughout history may have been doing just that. Alexander and colleagues identified a series of visual patterns – including contrast, grouping, incremental scaling, and symmetry – which, they contend, appear ubiquitously throughout global vernacular architecture precisely because of their inherent emotional appeal (Alexander, 1977, 2002; Salingaros, 2007). The proposed psychological benefits of these patterns are explored in the third chapter of this thesis. Further research is needed to understand the neural underpinnings of complex emotional responses to architecture like contemplation, comfort, curiosity, and awe.

In addition to emotions, aesthetics researchers often measure judgments as a means of gauging a participant's evaluative response to art or architecture. Subjects are typically asked to judge visual stimuli on dimensions such as beauty or attractiveness. In one study, beauty judgments of architecture were shown to vary with activity in various regions of the prefrontal cortex, including the frontopolar cortex and the superior frontal gyrus, as well as brain regions involved in memory retrieval, such as the parahippocampus (Vartanian et al., 2013). These neural regions are somewhat distinct from reward circuitry associated with emotions. Activation of the prefrontal cortex suggests that conscious reasoning and analysis can play a significant role in aesthetic judgment, while parahippocampal activation may mean that memories generated from education or past experience may influence this analytical process. Increased activity in both of these neural regions implies that aesthetic judgment may be

particularly influenced by inputs from the knowledge-meaning systems such as expertise, cultural trends, and an understanding of a building's intended function.

If evaluative and emotional responses to architecture involve distinct neural circuitry, then it would be reasonable to expect that what an occupant *thinks* about a building could be different from how they *feel* while spending time there.<sup>9</sup> These two dimensions of architectural experience could also have important influences on each other. For example, Di Dio and colleagues found that aesthetic judgment tasks actually diminish emotional responses to visual art. Participants who were asked to rate the beauty of Renaissance sculptures showed decreased activation in the right insula compared to those who were merely instructed to passively observe the sculptures (Di Dio, Macaluso, & Rizzolatti, 2007). Understanding potential interactions between aesthetic emotion and evaluation will be an important area of inquiry for future research in the neuroscience of architecture.

### **Automatic vs. non-automatic processing**

It is important to introduce the psychological concepts of *automatic* and *non-automatic* processing. Given the prevalence of these concepts in the environmental psychology literature, it is necessary to discuss how they relate to the neural systems presented in this chapter.

*Automatic* processing refers to the processing of sensory information from the environment that occurs independently of cognition. In this form of unconscious processing, the brain “automatically” assembles pieces of sensory information from an environmental stimulus and forms a response to that stimulus (e.g. an aesthetic response to a building) in a bottom-up fashion. Many of the sensory-motor response mechanisms described in the first section of this chapter (sensory-motor systems) could be categorized under the heading of *automatic processing*. For instance, the observed phenomenon of immobilization in response to a participant viewing images of tall buildings could be categorized as a type of *automatic* response if one could prove that this response occurs independently of cognition. As

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<sup>9</sup> By no means is this a new idea. The merits of these distinct modes of architectural experience, thinking and feeling, were famously argued by two leading architectural theorists, Christopher Alexander and Peter Eisenmann, in a heated debate at Harvard University in 1982.



discussed, research also suggests that some types of emotional responses to environmental stimuli may in fact occur in an automatic fashion (Hietanen & Korpela, 2004; Joye & Dewitte, 2016; K. M. Korpela, Klemettilä, & Hietanen, 2002; Valtchanov & Ellard, 2015). Thus, emotion-valuation neural systems are also relevant to the idea of automatic processing. Many key frameworks of environmental psychology focus on automatic processing mechanisms, including Wilson's biophilia hypothesis (Wilson, 1984), Ulrich's stress reduction theory (Ulrich, 1993), and Joye's theory of processing fluency (Joye, Steg, Ünal, & Pals, 2016; discussed in Chapter 5).

By contrast, the concept of top-down or *non-automatic* processing describes mechanisms of psychological responses to environmental stimuli that are mediated by cognition. Many of the studies presented in the previous section on knowledge-meaning systems involve top-down processing mechanisms. For instance, the finding that architectural education influences aesthetic preferences of buildings (Kirk, Skov, Christensen, & Nygaard, 2009) suggests that aesthetic evaluations can involve non-automatic processing mechanisms, i.e. cognitive assessments shaped by architectural education. Similarly, the influence of cultural upbringing on architectural experience (Konecni, 1979; Jacobsen, 2002; Ritterfeld, 2002) represents another type of top-down or *non-automatic* processing mechanism that is also likely mediated by knowledge-meaning systems in the brain. Cultural values that are learned through upbringing and experience shape how a person perceives and responds to the built environment, presumably in a top-down fashion.

One foundational framework for *non-automatic* processing of the environment is Brunswick's lens model (Brunswick, 1952). According to this framework, humans do not experience the environment directly and completely. Instead, they perceive a subset of cues from the external world that individually provide imperfect information about a given environment or stimulus. A person can then combine the information that they gather from the individual cues in order to form a more holistic judgment about the environment or stimulus to which they are responding (Brunswick, 1952). While this framework has most often been applied to human decision-making (Brunswick et al., 2000), the theory is also applicable to help explain the psychological mechanisms of top-down processing in aesthetic evaluations of architecture. For instance, an architect's education could influence her to notice certain cues (e.g. art deco design elements) in a building's façade that a non-architect would be less likely

to recognize. The recognition of these additional cues, as shaped by her education, would in turn influence the holistic judgment that she makes about the building (for instance, a judgment about the beauty of the façade). Working within this framework, one could postulate that factors such as education and cultural learning can influence a person's judgement of architecture by altering the types of cues available to them when they interact with the built environment.

The concepts of *automatic* vs. *non-automatic* processing are discussed here because they are widely used in the environmental psychology literature. However, they are not the focus of the present chapter due to the author's view that these terms are not grounded in neuroscientific evidence of how neural processing of the environment actually occurs. Instead of focusing on these binary concepts of neural processing, the author has instead presented a tripartite neural model involving three distinct but interacting neural systems. Rather than suggest that an architectural experience is the product of *either* automatic *or* non-automatic processing, the author instead suggests that psychological responses to the built environment are formed from integration of neural processing in sensory-motor, knowledge-meaning, and emotion-valuation systems. It is the author's view that the coordinated involvement of these three systems involves *both* automatic *and* non-automatic processing. This view is consistent with other published models of neuroaesthetics (Chatterjee & Vartanian, 2014; Leder et al., 2004; Leder & Nadal, 2014). It is the author's view that a neural systems-based model of architectural experience advances the debate beyond the qualitative frameworks of automatic vs. non-automatic processing of the environment.

### **Nature vs. nurture**

The neural model outlined here offers a way of reframing the fundamental "nature vs. nurture" question in neuroscientific terms. Scholars have long debated the question of whether biologically-based processes (nature) or culturally-rooted phenomena (nurture) play a more important role in shaping architectural experiences. On one side of this argument lies a body of empirical evidence suggesting that certain sensory features of the physical environment, such as fractal patterns (Salingaros, 2007) and self-similar forms (Alexander, 2002), may yield predictable response patterns in the human brain. Examples of this line of thinking include Appleton's *habitat theory* (Appleton, 1975) and Wilson's *biophilia hypothesis*

(Wilson, 1984), as described in the discussion of Sensory-Motor systems above. These biologically-based approaches align with Burke's sensory-based view of beauty perception (Burke, 1767), Alexander's belief in universal phenomenological responses to living structure (Alexander, 2002), and Fechner's philosophy of outer and inner psychophysics (Fechner, 1860). On the other side of the argument lies evidence that nurture-based factors like cultural context (Kirk, Skov, Hulme, Christensen, & Zeki, 2009), expertise (Kirk, Skov, Christensen, & Nygaard, 2009), and personal experience (Montoya, Horton, Vevea, Citkowicz, & Lauber, 2017) influence aesthetic responses to architectural design, as discussed in the Knowledge-Meaning section above. These findings are consistent with Eisenmann's emphasis on intellectually-based architectural experiences (Steil, 2004) and Bourdieu's view of aesthetics as a social construct (Bourdieu, 1984). Translating this philosophical debate into the language of neuroscience enables empirical assessment of the nature-nurture question, and findings on both sides of the argument have already started to emerge.

### **Challenges & future directions**

As outlined above, the neuroscience of architecture is poised to make a transition in which the prevalent descriptive approach can be extended and grounded in experimental research programs. Four challenges to this emerging discipline are outlined below, which are referred to as the nature vs. nurture, double framing, psychology, and measurement problems. Advances in each of these areas will provide structure to the field as it matures.

#### **Double framing**

This problem refers to the need for both general and specific frames to guide research. As mentioned earlier, having a theoretical framework is critical to placing experimental work in context. Without such a framework, individual studies remain isolated findings untethered to programmatic advances in understanding. Neuroaesthetics was helped by the introduction of general psychological and neuroscientific models that have since been debated and refined (Chatterjee, 2004a; Chatterjee & Vartanian, 2016; Jacobsen, 2006; Leder et al., 2004; Nadal, Munar, Capó, Rosselló, & Cela-Conde, 2008; Tinio, 2013). Here, one such general framework, the aesthetic triad, is applied to architecture. However, architectural spaces encompass different functions in a way that art typically does not. For a hospital, a school, a museum, a train station, and a home what makes the space beautiful might differ and be related to its

function. Furthermore, the context in which these spaces are experienced makes a difference. The anxiety of a patient in a hospital, the desire to learn in a school, the navigational demands of a train station, the comfort and safety of a home might all be relevant factors in the experience of a person within those spaces. This variability based on the purpose of the building and the inhabitants' expectations and states of mind need to be considered in any research involving the experience of such spaces.

### **Psychology of architecture**

Empirical aesthetics has a long and rich scholarly tradition of research in the psychology of aesthetics and the arts. This tradition includes Fechner's original contributions emphasizing the experience of the viewer as a critical variable in aesthetic understanding (Fechner, 1876), as well as Arnheim's perceptual psychology (Arnheim, 1954), Berlyne's concerns with complexity and arousal (Daniel E. Berlyne, 1971), and Martindale's historical-cultural analysis (Martindale, 1990), among many others. Neuroscientists can draw on this rich body of scholarship in guiding experimental work. While there are relevant pockets of research in environmental and human factors psychology (L. T. Graham et al., 2015; R. Kaplan & Kaplan, 1989), a similarly rich tradition of research situated specifically within a psychology of architecture does not exist. An insightful neuroscience of architecture likely cannot develop without a well-developed psychology of architecture, and the empirical studies presented in the subsequent chapters of this thesis aim to address this gap in the literature. Recent academic meetings also suggest that such a discipline might yet develop,<sup>10</sup> which would undoubtedly bolster the neuroscience of architecture.

### **Measurement challenges**

Four aspects of a neuroscience of architecture make measurement especially challenging. These aspects are dimensionality, multi-modality, temporality, and depth of psychological processing. To some extent these aspects are relevant to the neuroscience of art, but they are magnified when considering architecture.

Most neuroaesthetics research involves two-dimensional images. This makes sense when the stimuli viewed are flat paintings, although issues of scale and visual texture remain relevant

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<sup>10</sup> See, for instance, <http://www.psychologyofarchitecture.org/>

in so far as experiments are typically conducted on a computer screen in a laboratory. Even architecture-specific investigations have relied on flat visual stimuli to represent three-dimensional architectural space and thus might be treated more like artwork than buildings in these experiments. Real buildings induce more immersive and multisensory experiences than images of architecture or visual art. The specific experience of being in such a space might be more difficult to capture experimentally. A similar issue arises with installation art, which has not been investigated in any systematic way in neuroaesthetics. Perhaps in the near future virtual reality techniques will permit a reasonable approximation of the experience of immersion in an architectural space.

The multi-sensory nature of architectural experiences was mentioned earlier. Yet, research has focused primarily on visual aspects of architecture. How to incorporate different modalities and probe the neural underpinnings of an integrated sensory-motor experience remains a challenge to be addressed.

People often inhabit architectural spaces for hours or even days at a time. This ongoing engagement with space differs from our engagement with art. Investigators have probed early and a slightly later response to artwork, but such research is still confined to experiences that last less than a few seconds in duration (Cela-Conde et al., 2013). There is recognition that aesthetic experiences vary over longer durations than a few seconds (Chatterjee, 2014; Leder & Nadal, 2014), although the average museum patron spends less than twenty seconds engaging with works of art (Smith & Smith, 2001). Architectural encounters, by contrast, tend to be prolonged and are often habitual in the case of frequently visited buildings like one's home, school, or office. How best to sample neurophysiological data over time and "in the field" is a question that will need to be resolved over time (Gramann, Ferris, Gwin & Makeig, 2014). Mobile EEG has begun to be used in museum studies and innovative approaches to data collection have started to emerge (Kontson et al., 2015; Tröndle & Tschacher, 2012). These methods have great promise, although there remain technological issues of sampling and separating signal from noise, as well as theoretical issues of how best to use such technology in a hypothesis-testing framework.

Within empirical aesthetics there is an increasing appreciation that the field needs to expand its scope beyond the study of simple preferences to include a focus on deeper and more

complex psychological states (Silvia, 2012). This need is also relevant within the context of the neuroscience of architecture. For example, certain built spaces have the ability to facilitate deep contemplation that extends beyond mere preference, and it is important to understand design features that drive such effects. Other spaces might be designed to induce social cohesion, or to create a sense of refuge and comfort. Poorly designed spaces, by contrast, might increase an occupant's sense of alienation. The field would benefit from the development of ecologically valid approaches to measuring mental states that capture deep and nuanced psychological engagement with built spaces. The next chapter of this dissertation explores in greater depth the multifaceted psychological dimensions of architectural experience.

### Conclusion

Philosophers since ancient Roman times have emphasized the experiential importance of architectural aesthetics. Only in the past decade or so have scientists started to investigate this topic with rigor. This chapter outlined how an existing neural model – the aesthetic triad – can serve as a useful initial framework for researching *venustas*, the relatively neglected dimension of the Vitruvian Triad. According to this framework, sensory and emotional response patterns shaped by bioevolutionary forces may form the foundation of architectural experience, but this experience is substantially modified by a person's education, cultural upbringing, and personal experience.

Despite individual differences, consistent patterns of neural activity are emerging from this line of research that in the future could help architects design more brain-informed buildings. Researchers in environmental psychology and social epidemiology have tried to identify design characteristics that might improve our physical and mental health. Increasing evidence from these investigations suggests that “attractiveness is a key element in how the built environment affects our wellbeing” (Cooper & Burton, 2014, p. 13). In conjunction with increased precision in defining design concepts (Stamps, 1999), the neuroscience of architecture is well positioned to study the biological underpinnings of architectural beauty.

# Chapter 3:

## Psychological responses to architectural interiors

### Introduction

The previous chapter explored how the nervous system mediates the relationship between architecture and occupant experience. A recent surge of interest in the neuroscience of architecture reflects a growing recognition of the brain's important role in perceiving and responding to architectural design (Marchette et al., 2015; Robinson & Pallasmaa, 2015; Vartanian et al., 2013). However, there has been relatively little foundational research to date on the psychology of architecture (L. T. Graham et al., 2015). Unlike other areas of neuroscience, such as neurolinguistics and neuroaesthetics, neuroarchitecture lacks an extensive behavioral literature from which to generate neurophysiological models and predictions. This study aims to advance the psychology of architecture in order to lay the groundwork for a more robust line of research on the neuroscience of architecture.

The following experiments address two questions. First, are there principal dimensions of psychological experience in response to architectural scenes? Second, do these psychological dimensions correlate with aesthetic features of architectural design? In Experiment 1, participants (n=800) rated 200 images of building interiors on semantic differential scales that have previously been identified in the environmental psychology and neuroaesthetics literature as important measures of architectural experience (see section below, “psychological response measures tested,” for a review of these semantic differential scales and their corresponding references in the literature). Through Principal Components Analysis (PCA), three components were identified that explained 90% of the variance in ratings: *fluency* (ease with which one organizes and comprehends an architectural space), *fascination* (the informational richness and interest generated from viewing an architectural space), and *hygge* (extent to which the architectural space feels warm and personal).<sup>11</sup> Whereas *fluency*

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<sup>11</sup> *Hygge* is a Danish word that describes “a feeling of coziness, warmth, and togetherness” (Wiking, 2017, p. 25) that is often felt in the presence of intimate spaces and social settings. This concept is further explored in the “discussion” section of this chapter.

and *fascination* are well-established dimensions in assessing natural scenes and visual art, *hygge* emerged as a new dimension in relation to architectural scenes.

Furthermore, the experimental stimuli were counterbalanced on three salient architectural variables - ceiling height, enclosure, and curvature - in order to test the influence of these design features on principal component scores. An ANOVA was performed on the data, revealing two notable results: 1) open scenes scored significantly higher than closed scenes on *fluency*, *fascination*, and *hygge*, and 2) *fascination* was significantly influenced by all three of the design features that were tested. These results were then replicated in a follow-up experiment. These results suggest that psychological responses to this set of architectural scenes are explained by dimensions of *fluency*, *fascination*, and *hygge*, and that design features of ceiling height, enclosure, and curvature may predictably alter these dimensions of architectural experience.

#### **Psychological response measures tested**

Viewing architectural spaces elicits a broad range of psychological experiences, from feelings of comfort and excitement to judgments of a building's age and style. While a number of behavioral scales have been tested in environmental design research, these disparate response measures remain disconnected from any cohesive psychological framework. Chapter 2, however, outlined a neuroscientific model of architectural experience, which serves as a useful starting point for framing research on the psychology of architecture. According to the *aesthetic triad* model (Figure 3.1), three neural networks generate aesthetic experiences in the built environment: knowledge-meaning, emotion-valuation, and sensorimotor systems. These neural networks align closely with three important domains of psychological processing: *cognition*, *emotion*, and *behavior* (Izard, Kagan, & Zajonc, 1988; Lench, Darbor, & Berg, 2013; Stangor, 2015).



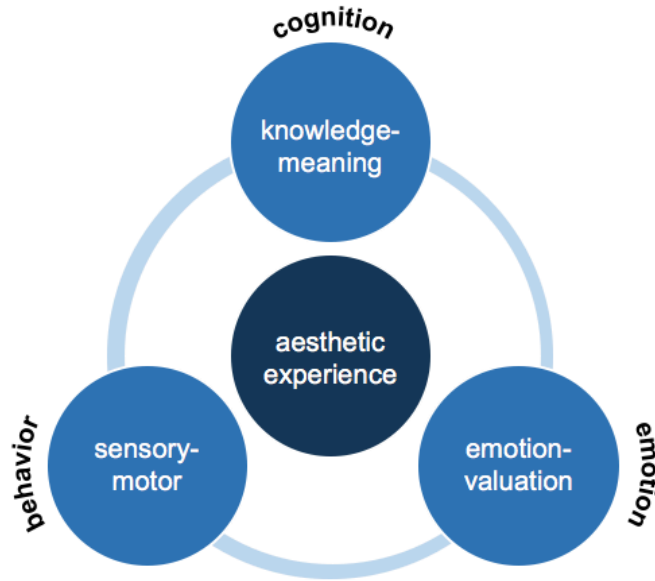


Figure 3.1: The *aesthetic triad* and associated psychological domains (adapted from Chatterjee & Vartanian, 2014; also published in Coburn et al., 2017).

Using this adapted terminology, it is proposed that architectural encounters produce three general classes of psychological experiences: *cognitive judgements* associated with knowledge-meaning systems, *emotional responses* derived from emotion-valuation networks, and *behavioral-motivational responses* linked to sensorimotor activation.<sup>12</sup> Within this psychological framework, sixteen semantic differential scales were chosen that capture important dimensions of architectural experience. These dependent measures were chosen because they have featured prominently in previous environmental psychology and empirical aesthetics research. The subsequent experiments identify the principal components of these response measures and explore how these psychological components relate to three aesthetic features of architectural scenes – ceiling height, enclosure, and curvature.

Originally, the author considered including up to thirty semantic differential scales that have featured in past environmental psychology literature, but resource limitations required him to reduce the number of measures to sixteen. Some of these measures were excluded from the analysis due to perceived redundancy. For instance, *coziness* was predicted to overlap

<sup>12</sup> While these three categories are meant to serve as a useful conceptual framework for organizing empirical research, the proposed relationships between the psychological domains and the neural networks should not be interpreted as exclusive. For instance, cognitive judgements about architecture involve sensory and emotional inputs, and behavioral responses depend on emotional and cognitive processing in addition to sensorimotor activity. Although some response measures may be influenced more by one network than another, most psychological experiences discussed here likely arise from integrated activity among all three neural systems.

significantly with *comfort*, so the more general term *comfort* was chosen. *Arousal* has featured prominently in the environmental psychology literature (Russell, Weiss, & Mendel, 1989). However, this measure has traditionally been awkward to operationalize, so the more fluid term *stimulation* was chosen to capture a similar type of environmental experience. Other measures, such as *fear*, were excluded because in the environmental psychology literature they have often been discussed in the context of outdoor environments rather than interior, built spaces. While fear-inducing architectural interiors certainly do exist, the author made the judgment that this emotional response seemed too extreme to apply to the image set used in this study. Very few if any of the images were expected to induce fear, and given the limited availability of funding for the study, this response measure was therefore excluded from the analysis.

#### *Cognitive judgements of architecture*

When people enter buildings, they often make cognitive judgments about the spaces around them. Cognitive judgments are defined here as top-down evaluations occupants makes about external qualities of their surroundings, rather than self-reflective evaluations of their own inner states of being. This distinction is based on past research suggesting that extrospective and intropective evaluations likely involve dissociable neural circuitry (Di Dio et al., 2007; Leder et al., 2004). Below, five key dimensions of cognitive judgement in the built environment are discussed.

The topic of visual *complexity* has drawn attention from many architectural theorists (Alexander, 2002; Kroll, 1987; Salingeros, 2007; Venturi, Scully, & Drexler, 1977), environmental psychologists (R. Kaplan & Kaplan, 1989; S. Kaplan, Kaplan, & Wendt, 1972; Ulrich, 1983), and aesthetics researchers (Daniel E. Berlyne, 1971; Frith & Nias, 1974). Visual complexity refers to “the volume of information present in a space” (Dosen & Ostwald, 2016, p. 3) and the informational “richness” of a scene (R. Kaplan & Kaplan, 1989, p. 53). Strong correlations between complexity and preference have been found in various contexts, including the evaluation of artwork (Day, 1967; Leder et al., 2004; Taylor, Micolich, & Jonas, 1999), natural landscapes (S. Kaplan, 1987; Ulrich, 1977, 1983), and built environments (Ç. Imamoglu, 2000; S. Kaplan et al., 1972). In many cases, preference ratings follow a U-shaped curve when plotted as a function of stimulus complexity (Daniel E. Berlyne, 1970, 1971; Güçlütürk et al., 2016; Taylor et al., 1999).

Perception of *organization* is also critical to the psychology of architecture. Visual order implies both an absence of randomness (Tullett, Kay, & Inzlicht, 2015) and the presence of predictable patterns like symmetry (Alexander, 2002; Reber et al., 2004; Salingaros, 2007) and structural redundancy in scenes (Kinchla, 1977; Kotabe et al., 2016b). The psychological effects of visual organization have been discussed extensively in architectural theory (Alexander, 2002; Salingaros, 2007; Vitruvius Pollio et al., 1914) and art aesthetics literature (Birkhoff, 1933; Eysenck, 1957; Reber et al., 2004). Perception of order can also be modulated by a building's age, condition, and architectural style. These dimensions have been captured in past studies by measuring subjects' perceptions of *modernity* in the built environment (Acking & Kuller, 1973; Ç. Imamoglu, 2000; V. Imamoglu, 1979).

Interacting with natural environments enhances many aspects of psychological functioning (Berman et al., 2012; Berto, 2005; Bratman, Daily, et al., 2015; S. Kaplan, 1995; Ryan et al., 2010), and evidence suggests that *naturalness* is a salient measure of environmental judgement (Berman et al., 2014; Kotabe, 2016) that correlates highly with scene preference ratings (Kardan, Demiralp, et al., 2015). Recent studies have also shown that the perception of naturalness is not merely determined by natural semantic content (e.g. recognition of trees and vegetation) but is also predicted by low-level visual patterns that can occur in both natural and man-made environments (Berman et al., 2014; Kardan, Demiralp, et al., 2015; Kotabe, 2016). Indeed, several scholars have proposed that nature-like aesthetic qualities are present, to varying degrees, in the built environment, and that naturalistic architectural spaces may confer some of the same psychological benefits as natural landscapes (Alexander, 2002; Joye, 2007b; Kellert, 2003; Salingaros, 1998).

*Beauty*, which is perhaps the most global measure of aesthetic judgment, is among the most frequently measured perceptual qualities in empirical aesthetics (Chatterjee, 2013; Ishizu & Zeki, 2011; Leder & Nadal, 2014; Nadal et al., 2010). Beauty has long been regarded as an important quality of architectural design in cultures around the world (Mak & Thomas Ng, 2005; Patra, 2009; Vitruvius Pollio et al., 1914). Efforts to understand environmental beauty have gained traction in both environmental psychology (Cooper, Burton, & Cooper, 2014; S. Kaplan, 1987; Zhang, Piff, Iyer, Koleva, & Keltner, 2014) and architectural research (Kirk, Skov, Christensen, et al., 2009; Vartanian et al., 2013, 2015), perhaps due to the growing perception

that “attractiveness is a key element in how the built environment affects our wellbeing” (Cooper & Burton, 2014).

Although these five response measures have been categorized here as cognitive judgments, it is likely that they depend on input from all three nodes of the aesthetic triad, rather than from cognitive processing alone. For instance, low-level spatial and color features of environmental scenes have been shown to significantly predict subjective ratings of complexity, order, and naturalness (Berman et al., 2014; Kardan, Demiralp, et al., 2015; Kotabe et al., 2016b; Kotabe, Kardan, & Berman, 2017), even when the semantic content of scenes is removed (Kotabe, Kardan, & Berman, 2016a; Kotabe et al., 2016b), suggesting that these perceptual measures are strongly shaped by low-level sensory input. Furthermore, perceptions of beauty likely involve complex interactions among sensory, emotional, and cognitive inputs (Chatterjee & Vartanian, 2014; Leder & Nadal, 2014; Leder et al., 2004).

#### *Emotional responses to architecture*

In addition to eliciting external judgments, architectural spaces can also modulate affect, emotions, and other inner states of being. Alexander (2002) emphasized the importance of judging a building not only via detached observation of its appearance, but also by examining the degree to which it “touches us in our humanity” (Alexander, 2002, p. 300) and “stirs our feelings, our passion” (Alexander, 2002, p. 302). Several other writers have also highlighted the introspective dimension of architectural experience (Bachelard, 1994; Heidegger, 2013; Linnet, 2012; Tanizaki, 2001).

The degree of personal feeling that a building generates is an important consideration in architectural design (Alexander, 2002; L. T. Graham et al., 2015; Sommer, 1969; Wiking, 2017). *Personal* spaces feel warm and intimate (L. T. Graham et al., 2015; Sommer, 1969) and generate feelings of “depth, tenderness, and longing” (Alexander, 2002, p. 302), whereas impersonal spaces often feel cold and standardized (Linnet, 2012). A related dimension, the degree to which an architectural space makes a person feel cozy or “at home” (Daniels, 2015; L. T. Graham et al., 2015; Ritterfeld & Cupchik, 1996), is captured by the Canadian concept of *hominess* (Linnet, 2012; Wiking, 2017). Considerable emphasis has also been placed on the degree of stress or, conversely, *relaxation* that people experience in response to environmental design (Baum & Davis, 1980; Fich et al., 2014; L. T. Graham et al., 2015; Tullett

et al., 2015; Tyrväinen et al., 2014; Ulrich et al., 1991). *Comfort* is also a salient measures of occupant experience that abounds in architectural research (Baker & Standeven, 1995; Brager et al., 2004; Fanger, 1973; Nicol & Humphreys, 2002; Thorsson et al., 2007).

Researchers have taken interest understanding how design parameters can modulate the degree of physiological *stimulation* that occupants experience (Acking & Kuller, 1973; L. T. Graham et al., 2015; Ritterfeld & Cupchik, 1996). This variable is closely related to the dimension of *arousal* that has featured prominently in environmental psychology literature (Russell, Weiss, & Mendel, 1989). However, *stimulation* was chosen because it can be operationalized more easily in a questionnaire. A related measure is the extent to which a place feels *uplifting*, on the one extreme, or depressing, on the other (Evans, 2003). This scale may be particularly relevant to wellbeing, as the frequency of daily uplifts a person experiences is predictive of long-term health measures like stress and depression (Kanner, Coyne, Schaefer, & Lazarus, 1981; Vitaliano, Scanlan, Ochs, & Syrjala, 1998). Scholars have also measured the impact of environmental design on *vitality* (Ryan et al., 2010; Tyrväinen et al., 2014), which also covaries with important physiological and psychological health measures (Ryan & Deci, 2008; Ryan & Frederick, 1997). Vitality has been defined as “a positive sense of aliveness and energy” (Nix et al., 1999, p. 530) and is closely related to the Chinese concept of *chi*, which Nix and colleagues defined as a source of calm energy that “can be more or less accessed by individuals depending on their lifestyles and personal practices” (Nix et al., 1999, p. 268). A related but broader measure, *valence*, describes the degree to which an architectural space makes an occupant feel good or bad. Valence is among the most frequently studied affective dimensions in empirical aesthetics and is closely related to other common measures such as preference, liking, and pleasantness (Acking & Kuller, 1973; Daniel E. Berlyne, 1970; Di Dio et al., 2007; Leder et al., 2004).

Although these affective response scales are associated with neural networks regulating pleasure and emotion, it is likely that cognitive and sensory processes also influence emotional dimensions of architectural experience. For instance, *hominess* ratings are likely modulated by cognitive evaluations based on an individual’s culture, upbringing, and memories of home. Pleasure responses to architectural scenes have also been shown to depend on education and expertise (Kirk, Skov, Christensen, et al., 2009), suggesting that *valence* may be influenced by top-down cognitive processing.

### *Behavioral-motivational responses to architecture*

The final class of architectural response scales encompasses the psychological measures of behavior, movement, and motivation, which may be linked to sensorimotor processing in the brain. *Interest*, an important response measure in empirical aesthetics (Daniel E. Berlyne, 1971; Day, 1967; Silvia, 2005, 2012) and environmental psychology (R. Kaplan & Kaplan, 1989; Ulrich, 1983), is closely linked to sensory perception (Day, 1967) and motivation (Silvia, 2008). James (1892) described interest as an automatic psychological process that enables us identify and attend to sensory stimuli that are important for our welfare. Environmental psychologists later applied this idea to landscape perception by proposing that sensory features of the environment are more likely to capture human interest if they have proven beneficial or detrimental to our species' survival over the course of evolutionary history (Appleton, 1975; S. Kaplan, 1987; E. O. Wilson & Kellert, 1995).

Interest can also motivate motor responses to physical surroundings (Joye & Dewitte, 2016; R. Kaplan & Kaplan, 1989; Ulrich, 1983), including fundamental decisions to *approach* or avoid architectural spaces (Ritterfeld & Cupchik, 1996; Vartanian et al., 2013, 2015). Another important behavioral response to architecture is “the need to *explore*, to find out more about what is going on in one's surroundings” (R. Kaplan & Kaplan, 1989, p. 51).

Although these response measures are associated with sensorimotor processing, they likely involve input from cognitive and affective domains discussed previously. Despite being strongly influenced by sensory content, *interest* has often been described as a measure of emotion (Silvia, 2005, 2008, 2012) and could justifiably be categorized as an affective response measure. Like valence and beauty, *approachability* describes a rather global psychological response that is likely modulated by cognitive and emotional processes.

### **Architectural variables**

Three architectural variables were chosen for investigation in this study: ceiling height, enclosure, and curvature. These three variables were chosen because they have been widely studied in the literature, and all three have consistently been found to correlate with psychological and neural response patterns in past research (Bar & Neta, 2006; Dazkir & Read, 2012; Fich et al., 2014; Leder & Carbon, 2005; Meyers-Levy & Zhu, 2007; Stamps, 2011; Vartanian et al., 2013, 2015). This variable choice therefore increased the likelihood that

there would be sufficient variation both in the architectural features of the stimuli and in the psychological responses to the stimuli. Furthermore, the stimulus set chosen for this study was pre-counterbalanced on these three architectural variables. This stimulus set was selected, in part, in order to explore correlations between self-reported psychological responses and neural response patterns, and the same stimulus set was used in two previous neuroimaging studies (Vartanian et al., 2013; Vartanian et al., 2015). Data was therefore available for item-level analysis comparing these past neuroimaging results with the psychological responses of the present experiment (these analyses are presented in Appendix A).

These three architectural variables are not meant to be exhaustive. By choosing these three variables, the author is also not attempting to suggest that these are the three most “important” features of the built environment with respect to psychological experience. Rather, these variables were chosen simply to ensure that there was some degree of variation in aesthetic features across the image set. Since all of these variables have been shown to correlate significantly with psychological responses in many previous studies (Bar & Neta, 2006; Dazkir & Read, 2012; Fich et al., 2014; Leder & Carbon, 2005; Meyers-Levy & Zhu, 2007; Stamps, 2011; Vartanian et al., 2013, 2015), and because previous neuroimaging data involving these variables (Vartanian et al., 2013, 2015) was available to the author, they were appropriate measures to include in the present research. Other architectural variables that have been shown to relate to psychological experience include the presence or absence of windows (Fich et al., 2014; Kaye & Murray 1982), warmth (Hidayetoglu et al., 2012) and intensity (Berman et al., 2014; Kardan et al., 2015) of colors, the relative presence of architectural detail and ornamentation in a building (Alexander, 2002; Salingaros, 2007; Kellert, 2005), to name just a few examples. Some of these additional variables are further explored in Chapters 4 and 5 of the thesis.

#### *Ceiling Height*

Research suggests that *ceiling height* can significantly affect psychological responses to architectural interiors. In a recent study investigating the effect of ceiling height on aesthetic perceptions and neural activity, spaces with high ceilings received significantly higher beauty

ratings than those with low spaces. Functional Magnetic Resonance Imaging (fMRI)<sup>13</sup> results showed that rooms with high ceilings differentially activated neural structures involved in visuospatial attention and exploration, such as the left middle frontal gyrus (a region in the frontal lobe of the brain) and left precuneus (a region in the parietal lobe of the brain) (Vartanian et al., 2015). These findings were consistent with previous research indicating that high ceilings increase perceptions of spaciousness (Stamps, 2011) and prime thoughts of freedom, whereas low ceilings are more likely to prime thoughts of confinement (Meyers-Levy & Zhu, 2007). Baird and colleagues (1978) found that, on average, occupants' preferences for ceiling height peak around 10 feet across a range of spatial functions (Baird, Cassidy, & Kurr, 1978).

#### *Enclosure*

Spatial *enclosure* has been found to modulate aesthetic and psychological responses to building interiors. Appleton's prospect-refuge theory (1975) proposed that humans have evolved innate preferences for environments which offer opportunities to see (points of prospect) without being seen (points of refuge). Such places, he argued, have historically proven beneficial to our species survival by enabling humans to see and hide from threats (Appleton, 1975). In support of this theory, evidence suggests that humans generally to feel safer in more open spaces (Stamps, 2005) and also tend to prefer interior environments that afford greater visual connection with external surroundings (Vartanian et al., 2015), when controlling for other factors.

In a study of psychological and neural responses to open and enclosed architectural interiors, participants were more likely to want to approach open rooms and to rate those rooms as beautiful in comparison to enclosed interiors. Open spaces also activated neural areas associated with perceived visual motion, whereas enclosed surroundings activated neural regions involved in fear processing (Vartanian et al., 2015). This finding was theoretically consistent with results from a previous study indicating that enclosed spaces, relative to open

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<sup>13</sup> fMRI is a technology that measures neural activity by monitoring changes in blood flow to different areas of the brain. Since neuronal activation and blood flow are coupled, increased blood flow to a certain brain region implies greater neural activity in that region.



environments, can increase vulnerability to stress and also prolong an occupant's stress response following exposure to an induced stress test (Fich et al., 2014).

#### *Curvature*

Geometric contour, or *curvature*, has generated much interest from aesthetics and architectural researchers. In many contexts, people have exhibited greater preferences for curvilinear objects than their rectilinear objects (Bar & Neta, 2006; Dazkir & Read, 2012; Leder & Carbon, 2005). Rectilinear shapes and patterns have also been shown to evoke more unpleasant emotions compared to curvilinear forms (Hevner, 1935; Lundholm, 1921; Poffenberger & Barrows, 1924). These perceptual trends may also extend to the built environment. A study on the perception of architectural contour, for instance, found that curved building interiors were judged as more beautiful than rectilinear spaces. Curved buildings also activated key areas of the visual cortex, including the lingual and calcarine gyrus, when subjects made approach-avoidance decisions (Vartanian et al., 2013).

#### **Research questions**

Two research questions motivated this study. First, what are the primary psychological dimensions underlying visual responses to interior architectural scenes? Second, how do ceiling height, enclosure, and curvature modulate these responses? To answer the first question, participants were asked to rate images of building interiors on 16 psychological measures that capture important aspects of architectural experience. A principal components analysis was then carried out to identify the latent psychological dimensions that explained the most variance across the original 16 measures. The second research question was addressed by counterbalancing the stimuli on three architectural variables of interest and carrying out ANOVAs to determine the degree to which these spatial properties influenced psychological experiences. A second experiment was carried out to test the ecological validity of the first study by replicating the PCA results with a new group of participants.

## Experiment 1: Psychological dimensions of architectural experience

### Methods

#### *Materials*

The stimuli for this experiment were 200 photographs of interior architectural spaces. These same images were previously used in two previous studies (Vartanian et al., 2013, 2015). The stimuli were selected from image databases at the Department of Architecture, Design, and Media Technology of Aalborg University and The Royal Danish Academy of Fine Arts School of Architecture. The scenes selected for the study varied on three environmental parameters. Half of the rooms depicted in the images were enclosed, while the other half were open. In this study, “enclosed” spaces were defined as images of rooms that lacked any visible permeability to the outside, and “open” spaces were those that featured permeable openings to the outside (e.g. windows, doorways, etc.). Half had high ceilings and half had low ceilings. Finally, half of the interiors had curvilinear edges (“round” condition), while the other half were rectilinear (“square” condition). This setup yielded the eight experimental conditions outlined in Figure 3.2 (n = 25 per condition): closed square low, closed square high, closed curved low, closed curved high, open square low, open square high, open round low, and open round high.

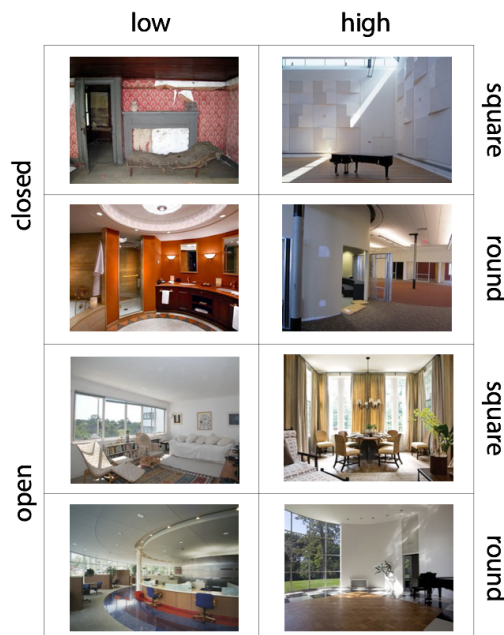


Figure 3.2: Eight experimental conditions (n = 25 per condition) were generated by varying three architectural parameters (ceiling height, enclosure, and curvature) across the stimulus set.

#### *Participants*

798 US-based adults (391 women, 401 men, 6 other) were recruited from Amazon's Mechanical Turk to participate in this study. Sample size was determined by the goal of obtaining approximately 50 ratings per image on each of the sixteen psychological dimensions measured. Ages ranged from 18 to 75 years ( $M = 38.06$ ,  $SD = 11.96$ ), and education level ranged from 5 to 22 years ( $M = 15.04$ ,  $SD = 2.11$ ). In terms of ethnicity, 619 participants identified as white, 96 as African American, 57 as Asian, 56 as Hispanic, 11 as American Indian or Alaskan Native, and 11 as Other. 712 participants identified as heterosexual, 27 as homosexual, 52 as bisexual, 4 as Other, and 10 did not report sexual orientation. 730 participants were right-handed and 72 were left-handed. Architectural experience of participants was assessed on a scale of 1 to 7, with 1 indicating "no experience," 4 indicating "average experience," and 7 indicating "expert." Self-reported architectural experience ranged from 1 to 7 ( $M = 2.8$ ,  $SD = 1.6$ ). These demographic data were collected in order to verify that the sample group was comprised of a diverse pool of participants representative of a randomly-selected sample from the US adult population. Participants were compensated \$4.00 for their participation and the experiment took approximately 40 minutes to complete. Informed consent was obtained through the IRB of the University of Pennsylvania. Four participants repeated the study twice. For each of these participants, data from the second round of testing was excluded from analysis.

#### *Procedures*

Participants collectively rated 200 images of architectural interiors on 16 psychological dimensions. In total, approximately 50 ratings were collected per image for each dimension. The stimuli were divided into four blocks of 50 images. Each image block contained an even distribution of images from each of the eight architectural conditions, with 6-7 randomly selected stimuli represented from each condition per block (Table 3.1). This blocking scheme ensured that participants had approximately equal exposure to each architectural condition for each rating task they completed. The psychological dimensions were also divided into rating groups, with four dimensions in each group. Sixteen rating groups were created, each containing a unique combination of four psychological dimensions (Table 3.2).

### CHAPTER 3: PSYCHOLOGICAL RESPONSES TO ARCHITECTURAL INTERIORS

**Table 3.1: Summary of stimulus distribution within each image block. Architectural conditions are labeled as follows: high ceilings (H), low ceilings (L), open (O), closed (C), square (S), round (R).**

	H-C-S	H-C-R	H-O-S	H-O-R	L-C-S	L-C-R	L-O-S	L-O-R	Total Images
<b>Block 1</b>	7	7	6	6	6	6	6	6	50
<b>Block 2</b>	6	6	7	7	6	6	6	6	50
<b>Block 3</b>	6	6	6	6	7	7	6	6	50
<b>Block 4</b>	6	6	6	6	6	6	7	7	50
<b>Total Images</b>	25	25	25	25	25	25	25	25	200

**Table 3.2: Rating groups for psychological rating scales.**

<b>Group 1</b>	<b>Group 2</b>	<b>Group 3</b>	<b>Group 4</b>	<b>Group 5</b>	<b>Group 6</b>	<b>Group 7</b>	<b>Group 8</b>
Complexity	<u>Personalness</u>	Stimulation	Homeyness	Organization	Interest	Vitality	Uplift
Organization	Interest	Vitality	Uplift	Naturalness	Modernity	Comfort	Approachability
Naturalness	Modernity	Comfort	Approachability	Beauty	Valence	Relaxation	Explorability
Beauty	Valence	Relaxation	<u>Explorability</u>	Personalness	Stimulation	Homeyness	Complexity
<b>Group 9</b>	<b>Group 10</b>	<b>Group 11</b>	<b>Group 12</b>	<b>Group 13</b>	<b>Group 14</b>	<b>Group 15</b>	<b>Group 16</b>
Naturalness	Modernity	Comfort	Approachability	Beauty	Valence	Relaxation	Explorability
Beauty	Valence	Relaxation	Explorability	Personalness	Stimulation	<u>Homeyness</u>	Complexity
Personalness	Stimulation	Homeyness	Complexity	Interest	Vitality	Uplift	Organization
Interest	Vitality	Uplift	Organization	Modernity	Comfort	Approachability	Naturalness

At the start of the experiment, participants were presented with a slideshow of all 200 images shown in random order. This was intended to familiarize them with the full range of stimuli before they rated any images. Subjects were subsequently assigned, at random, to one of the sixteen rating groups. They were then presented with one of the four image blocks and were asked to rate every image within that block on one of the four psychological dimensions from their assigned rating group. Next, they rated images from a second image block on a second psychological dimension, images from a third block on a third dimension, and images from the final block on the fourth dimension. Ratings were entered on a 7-point sliding semantic differential scale displayed below the image. Prompts and scale anchors are shown in Table 3.3. The presentation order of the four image blocks and the assigned order of the four rating tasks were randomized. Images within each block were also presented to subjects in a randomized sequence. This design allowed participants to experience a variety of rating tasks while minimizing the cognitive demands of frequent task-switching (Monsell, 2003). It also ensured that images received an equal number of ratings on each psychological dimension and minimized ordering effects by assigning diverse combinations of rating task sequences to different participants. After completing the study, participants were asked to fill out a brief demographics questionnaire.

**Table 3.3: Prompts and end anchors of 7-point rating scales for the psychological dimensions.**

Psychological dimension	Rating prompt	Low anchor	High anchor
Complexity	<i>This room looks...</i>	Simple	Complex
Organization	<i>This room looks...</i>	Disordered	Organized
Naturalness	<i>This room looks...</i>	Artificial	Natural
Beauty	<i>This room looks...</i>	Ugly	Beautiful
Personalness	<i>This room looks...</i>	Impersonal	Personal
Interest	<i>This room looks...</i>	Boring	Interesting
Modernity	<i>This room looks...</i>	Aged	Modern
Valence	<i>This room makes me feel...</i>	Bad	Good
Stimulation	<i>This room makes me feel...</i>	Bored	Excited
Vitality	<i>This room makes me feel...</i>	Lifeless	Alive
Comfort	<i>This room makes me feel...</i>	Uncomfortable	Comfortable
Relaxation	<i>This room makes me feel...</i>	Stressed	Relaxed
Hominess	<i>This room makes me feel...</i>	Alienated	At home
Uplift	<i>This room makes me feel...</i>	Diminished	Uplifted
Approachability	<i>If I saw this room, I'd...</i>	Leave	Enter
Explorability	<i>If I saw this room, I'd...</i>	Ignore it	Explore it

## Analysis & Results

All data analysis was carried out at the item level for this experiment. This was achieved by calculating the average rating for each image on every psychological dimension measured. Principal components analysis was then performed to determine the primary psychological components underlying the experience of viewing photographs of the 200 architectural interiors. Next, three-way factorial ANOVAs were calculated to determine the degree to which the three architectural variables predicted principal component scores.

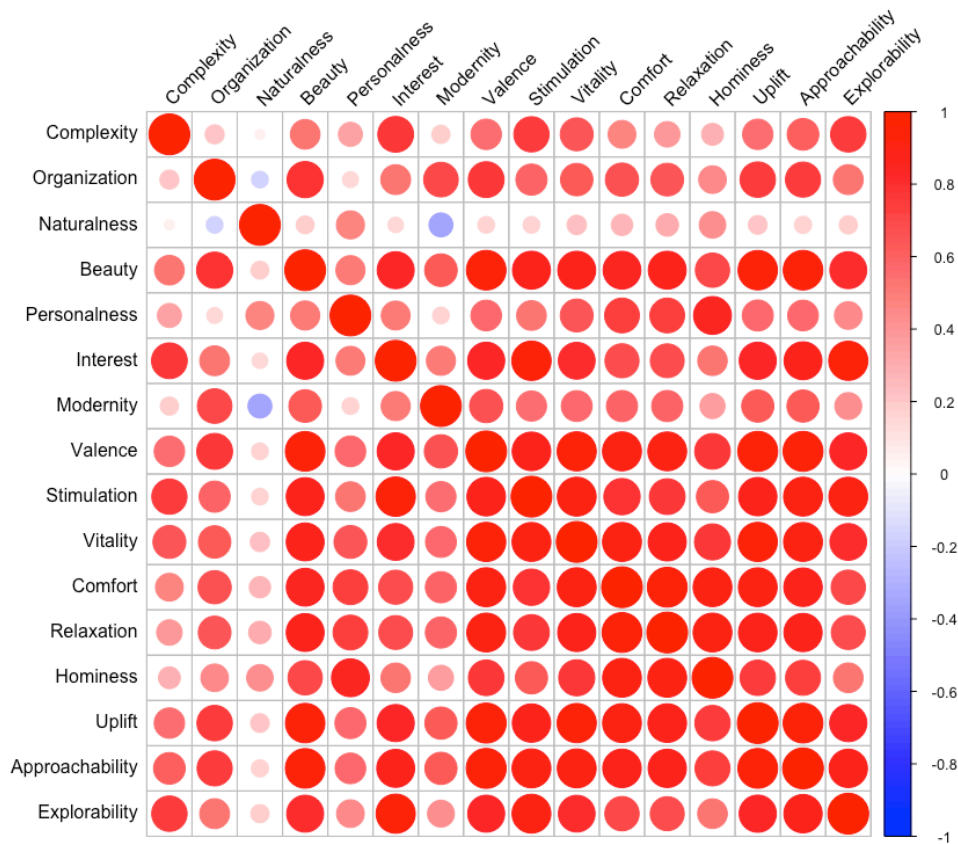
### *PCA of psychological dimensions*

Correlations were examined across the sixteen psychological dimensions using the *stats* (R Core Team, 2016), *corrplot* (Wei & Simko, 2016), and *psych* (Revelle, 2016) packages in R (R Core Team, 2016). The correlation matrix (Figure 3.3) revealed a high degree of covariance across many of the dimensions. The value for the determinant of the correlation matrix (DCM) was  $6.3 \times 10^{-14}$ .<sup>14</sup> This was substantially below the recommended minimum threshold of  $1 \times 10^{-5}$  (Field, Miles, & Field, 2014), indicating that the multicollinearity among the dependent variables was too high to perform an accurate factor analysis. To remedy this problem, six variables were excluded from factor analysis because each exhibited high bivariate correlations (above 0.9) with at least one of the retained variables.<sup>15</sup> The excluded variables

<sup>14</sup> The DCM was calculated using the *stats* R package (R Core Team, 2016).

<sup>15</sup> For further discussion of the methodological reasons for excluding redundant variables from factor analysis, see (Field, Miles, & Field, 2014, Chapter 17).

were vitality (0.92 correlation with valence), uplift (0.96 correlation with valence), comfort (0.91 correlation with valence), relaxation (0.91 correlation with valence), stimulation (0.93 correlation with interest), and explorability (0.92 correlation with interest). Modernity was also excluded from factor analysis to further reduce redundancy, and because it was deemed the least theoretically relevant of the remaining 10 psychological dimensions. After excluding these variables from the analysis, the DCM for the nine retained dimensions yielded a value of  $4.8 \times 10^{-6}$ , which was within an acceptable range of the recommended threshold (Field et al., 2014).



**Figure 3.3: Correlation matrix of 16 original psychological dimensions.<sup>16</sup>**

A principal components analysis (PCA) was performed on the 9 retained variables with oblique (oblimin) rotation.<sup>17</sup> The Kaiser-Meyer-Olkin (KMO) index score<sup>18</sup> of 0.83 confirmed

<sup>16</sup> Figure was created using the *stats* (R Core Team, 2016) and *corrplot* (Wei & Simko, 2016) packages in R.

<sup>17</sup> PCA was performed using the “principal” function in the *psych* R package (Revelle, 2016).

<sup>18</sup> The KMO was calculated using the “KMO” function of the *psych* package in R (Revelle, 2016).

the sampling adequacy for the PCA, and all KMO values for individual variables were above 0.63. Bartlett's sphericity test <sup>19</sup> indicated that correlations between variables were sufficiently high for PCA ( $\chi^2 = 2392$ ,  $p < .001$ ). An initial PCA was carried out with 9 components retained to determine eigenvalues for each component in the data. The first two components had eigenvalues above Kaiser's criterion of 1 and explained 80% of the variance, while the first three components had eigenvalues exceeding Jolliffe's criterion of 0.7 and together explained 90% of the variance. Since the sample size was less than 250, Jolliffe's criterion was deemed more appropriate and three components were retained.<sup>20</sup>

Table 3.4 shows the factor loadings, eigenvalues, and explained variance for each of the three retained principle components after oblimin rotation. The variables that cluster on each component suggest that PC1 represents processing *fluency*, PC2 represents the feeling of *hygge*, and PC3 captures the experience of *fascination*. Figure 3.4 displays the PCA results in graphical form. Each arrow represents a discrete psychological variable, and each axis represents a principal component. The size and direction of the arrows indicates the proximity of the original variables to the latent principal components.

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<sup>19</sup> Bartlett's test was run using the "cortest.bartlett" function of the *psych* package in R (Revelle, 2016).

<sup>20</sup> For further discussion of factor retention criteria for PCA, see (Field et al., 2014, Chapter 17)

Table 3.4: Factor loadings on the three retained principal components following oblimin rotation.

	PC1 (Fluency)	PC2 (Hygge)	PC3 (Fascination)
<b>Complexity</b>	-0.08	-0.06	<b>1.02</b>
<b>Organization</b>	<b>1.04</b>	-0.19	-0.12
<b>Naturalness</b>	-0.31	<b>0.90</b>	-0.04
<b>Beauty</b>	<b>0.76</b>	0.19	0.24
<b>Personalness</b>	0.10	<b>0.83</b>	0.11
<b>Interest</b>	0.37	0.08	<b>0.71</b>
<b>Valence</b>	<b>0.74</b>	0.22	0.26
<b>Hominess</b>	0.49	<b>0.73</b>	-0.09
<b>Approachability</b>	<b>0.69</b>	0.21	0.34
<b>Eigenvalue</b>	<b>3.57</b>	<b>2.39</b>	<b>2.16</b>
<b>Variance Explained</b>	<b>40%</b>	<b>27%</b>	<b>24%</b>
<b>Cumulative Variance</b>	<b>40%</b>	<b>66%</b>	<b>90%</b>

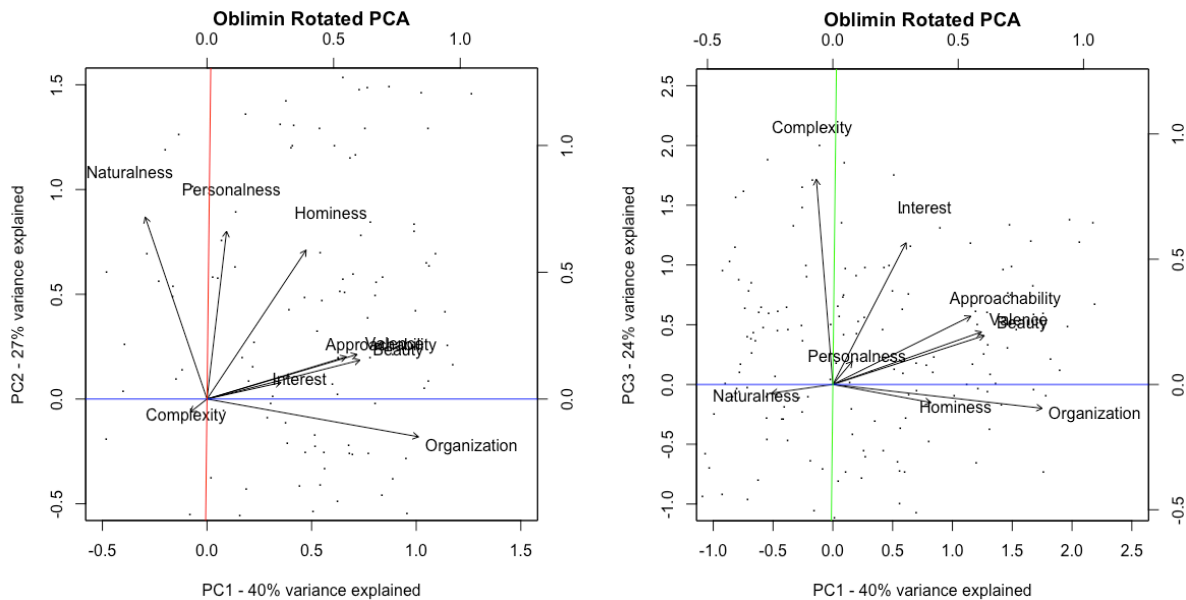


Figure 3.4: Factor loadings on the three retained principle components following oblimin rotation.<sup>21</sup>

### Determining the influence of architectural variables on psychological ratings

3-way factorial ANOVAs were carried out using the *stats* (R Core Team, 2016) and *ez* (Lawrence, 2016) R packages to determine the relationship between principle component scores and the three architectural variables of interest. Graphical and statistical results of this analysis are displayed in Figure 3.5. There were significant main effects of ceiling height ( $F = 13.56, p < .001$ ), enclosure ( $F = 5.21, p = .024$ ), and curvature ( $F = 14.94, p < .001$ ) on PC3 (*fascination*) as well as significant main effects of enclosure on PC1 (*fluency*) ( $F = 6.39, p =$

<sup>21</sup> Graphics were created using the “biplot” function of the *stats* R package (R Core Team, 2016).



.012) and PC2 (*hygge*) ( $F = 10.94$ ,  $p = .001$ ). No significant interaction effects were found among the three architectural variables.

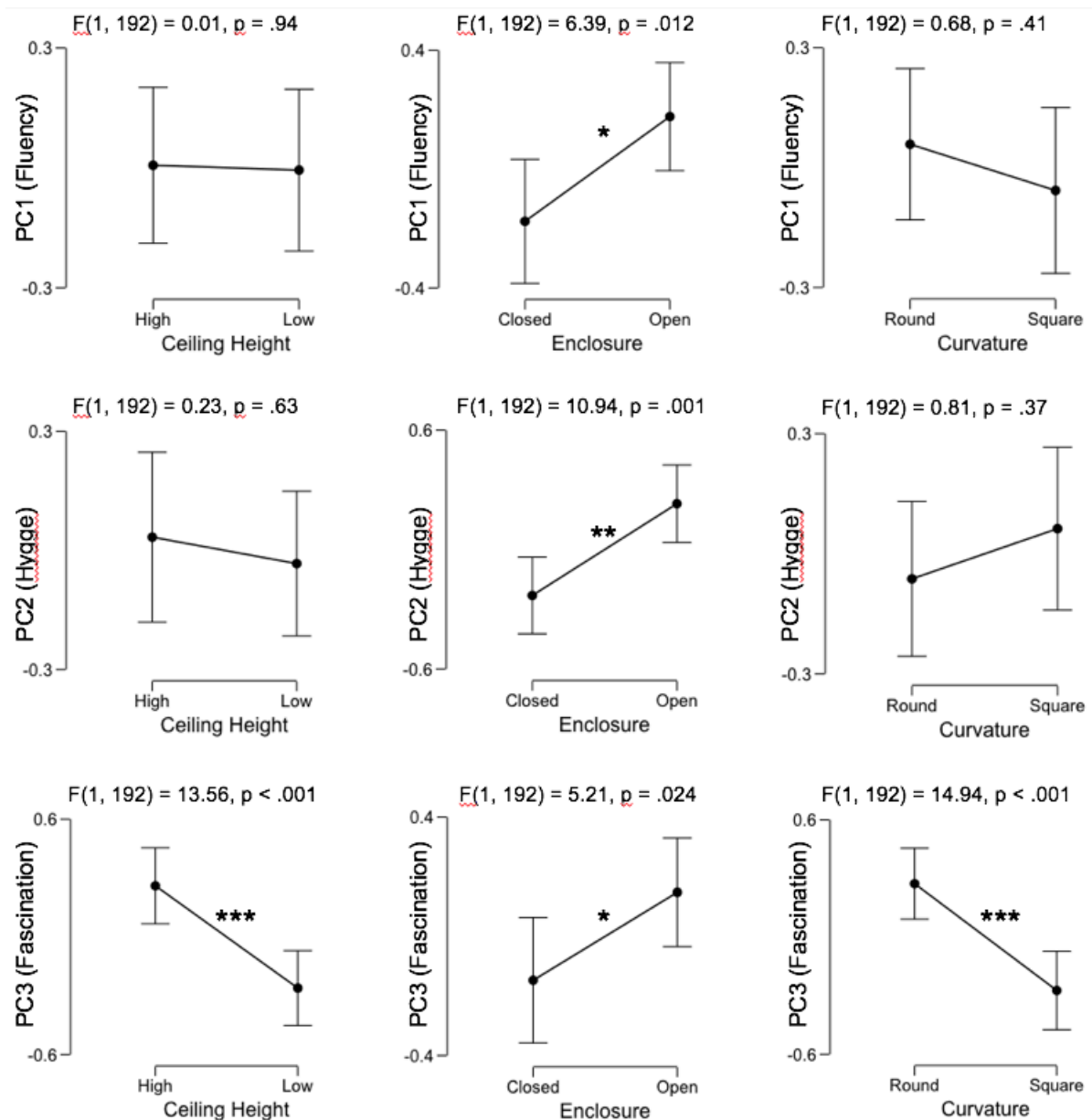


Figure 3.5: 3-way factorial ANOVA results and error plots of PCA scores as a function of architectural variables.<sup>22</sup>

<sup>22</sup> Graphic visualizations were created using the *ez* package in R (Lawrence, 2016).  $\eta_p^2$  values were calculated using the *lsr* package in R (Navarro, 2015).

## **Experiment 2: Replication of PCA results**

In Experiment 2, a replication study was conducted to investigate whether or not a different experimental design would yield the same three principal components as were found in Experiment 1. Whereas each participant in the first experiment rated all 200 architectural images on a subset of 4 psychological dimensions, participants in Experiment 2 were asked to rate a subset of architectural scenes on all 9 non-redundant psychological dimensions. This new design enabled a more robust PCA to be performed accounting for each participant's within-subject ratings for each architectural condition across all of the dependent measures of interest.

### **Methods**

#### *Participants*

614 American adults (305 women, 307 men, 2 other) were recruited from Amazon's Mechanical Turk to participate in this study. Data from 12 additional participants was excluded from analysis due to non-adherence to experimental instructions. Sample size was determined by the goal of obtaining approximately 50 ratings per image on each of the nine psychological dimensions measured. Ages ranged from 19 to 72 years ( $M = 35.68$ ,  $SD = 10.87$ ), and education level ranged from 2 to 26 years ( $M = 15.26$ ,  $SD = 2.31$ ). In terms of ethnicity, 477 participants identified as white, 60 as African American, 58 as Asian, 35 as Hispanic, 15 as American Indian or Alaskan Native, and 2 as Other. 545 participants identified as heterosexual, 17 as homosexual, 46 as bisexual, 4 as Other, and 2 did not report sexual orientation. 549 participants were right-handed and 65 were left-handed. Architectural experience of participants was assessed on a scale of 1 to 7, with 1 indicating "no experience," 4 indicating "average experience," and 7 indicating "expert." Self-reported architectural experience ranged from 1 to 7 ( $M = 2.8$ ,  $SD = 1.6$ ). These demographic data were collected in order to verify that the sample group was comprised of a diverse pool of participants representative of a randomly-selected sample from the US adult population. Participants were compensated \$2.40 for their participation and the experiment took approximately 20 minutes to complete. Informed consent was obtained through the IRB of the University of Pennsylvania.

### *Procedures*

The 200 architectural images were divided into the eight experimental conditions shown in Figure 3.2 ( $n = 25$  per condition): closed square low, closed square high, closed curved low, closed curved high, open square low, open square high, open round low, and open round high. Each of these 25-image conditions was then split into a low-beauty group and a high-beauty group, based on images' beauty scores from Experiment 1, yielding a total of 16 groups of images. Images that received the median beauty score within each 25-image condition were alternately assigned to either the low-beauty group or the high-beauty group for that condition.

Each participant was asked to rate a batch of 16 images on all nine dependent psychological measures. Batches were created by randomly selecting one image from each of the 16 groups. This design ensured that each subject rated one low-beauty image and one-high beauty image from each experimental condition. Subjects rated all 16 images on one dependent measure before moving onto the next rating task to minimize fatigue from frequent task-switching (Monsell, 2003). The order of image presentation was randomized within each individual rating task, and the order in which the nine ratings tasks were assigned was also randomized within each participant. After completing the study, subjects were asked to fill out a brief demographics questionnaire.

## **Analyses & Results**

### *PCA of psychological dimensions*

Correlations among the nine dependent measures were analyzed using the *stats* (R Core Team, 2016), *corrplot* (Wei & Simko, 2016), and *psych* (Revelle, 2016) packages in R (R Core Team, 2016). The correlation matrix (Figure 3.6) yielded a DCM value of  $7.7 \times 10^{-3}$ . This was above the recommended minimum threshold of  $1 \times 10^{-5}$  (Field et al., 2014), indicating that multicollinearities among the psychological variables were sufficiently low to perform a reliable factor analysis.

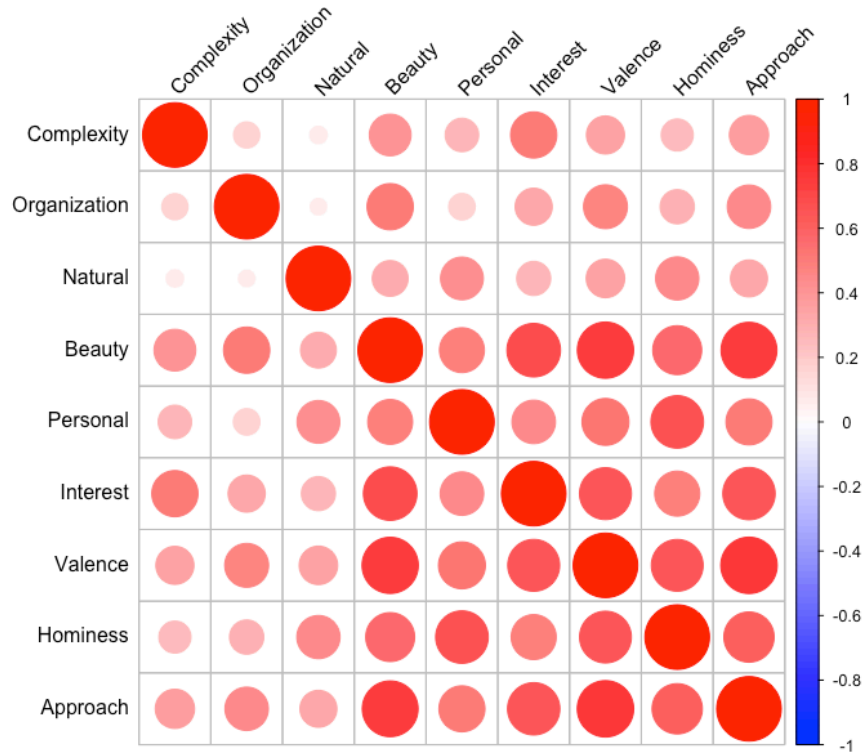


Figure 3.6: Correlation matrix of 9 psychological variables from Experiment 2.

A PCA was performed on the 9 dependent variables with oblique (oblimin) rotation.<sup>23</sup> The Kaiser-Meyer-Olkin (KMO) index score<sup>24</sup> was 0.9, confirming the sampling adequacy for the PCA. KMO values for all individual variables were above 0.86. Bartlett's sphericity test<sup>25</sup> showed that correlations among variables were sufficiently high for PCA ( $\chi^2 = 47843$ ,  $p < .001$ ). An initial PCA was carried out with 9 components retained to determine eigenvalues for each component in the data. The first three components had eigenvalues exceeding Jolliffe's criterion of 0.7 (Field et al., 2014) and together explained 76% of the variance. These three components were retained. Table 3.5 displays the factor loadings, eigenvalues, and variance explained for each of the three retained principle components after oblimin rotation. A similar factor structure emerged as was found previously in Experiment 1. In the replication, PC1 captured the feeling of *hygge*, PC2 represented processing *fluency*, and PC3 described the experience of *fascination*. Thus, Experiment 2 closely replicated the PCA results of Experiment

<sup>23</sup> PCA was performed using the "principal" function in the *psych* R package (Revelle, 2016).

<sup>24</sup> The KMO was calculated using the "KMO" function of the *psych* package in R (Revelle, 2016).

<sup>25</sup> Bartlett's test was run using the "cortest.bartlett" function of the *psych* package in R (Revelle, 2016).

1, with the exception that *hygge* explained more of the overall variance than *fluency* in the follow-up study.

Table 3.5: Factor loadings on the three principal components following oblimin rotation.

	PC1 (Hygge)	PC2 (Fluency)	PC3 (Fascination)
Complexity	-0.10	-0.10	<b>0.98</b>
Organization	-0.15	<b>0.97</b>	-0.13
Naturalness	<b>0.90</b>	-0.15	-0.19
Beauty	0.28	<b>0.57</b>	0.31
Personalness	<b>0.79</b>	-0.04	0.14
Interest	0.24	0.27	<b>0.59</b>
Valence	0.42	<b>0.53</b>	0.20
Hominess	<b>0.74</b>	0.20	0.04
Approachability	0.37	<b>0.52</b>	0.26
Eigenvalue	<b>2.73</b>	<b>2.28</b>	<b>1.83</b>
Variance Explained	<b>30%</b>	<b>25%</b>	<b>20%</b>
Cumulative Variance	<b>30%</b>	<b>56%</b>	<b>76%</b>

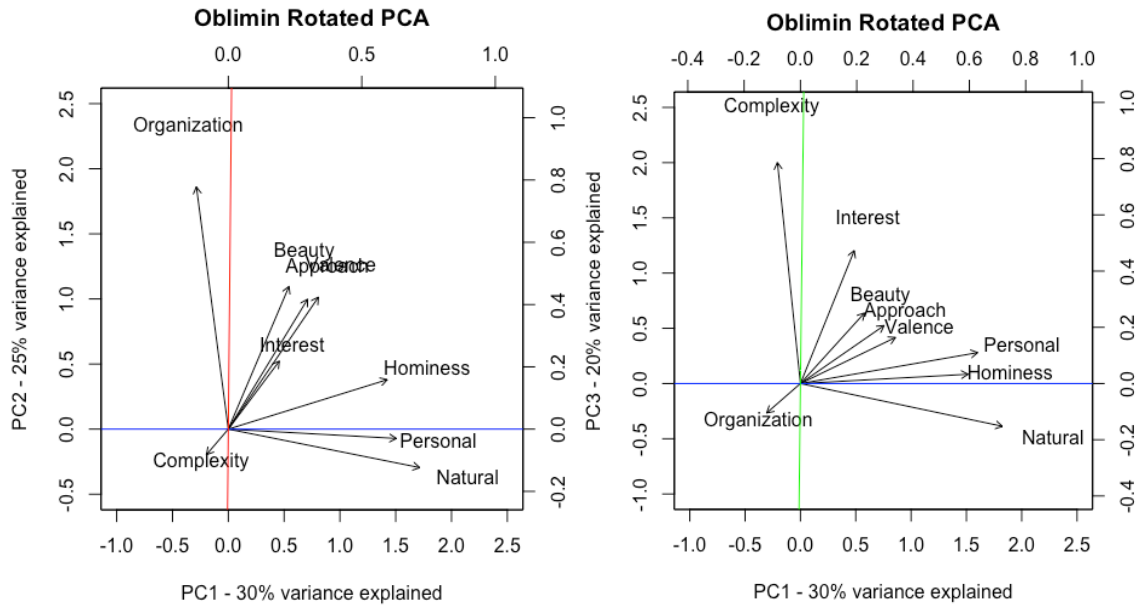


Figure 3.7: Factor loadings on the three principal components following oblimin rotation.

### Determining the influence of architectural variables on psychological ratings

3-way factorial ANOVAs were carried out using the ANOVA function in JASP statistical software (Wagenmakers, 2016) to determine the effect of the three architectural variables on principle component scores. Results of this analysis are displayed in Figure 3.7. There were significant main effects of ceiling height ( $F = 15.23, p < .001$ ), enclosure ( $F = 118.43, p < .001$ ), and curvature ( $F = 20.95, p < .001$ ) on PC1 (*hygge*). For PC2 (*fluency*), there were also significant main effects of ceiling height ( $F = 28.25, p < .001$ ), enclosure ( $F = 180.39, p < .001$ ), and curvature ( $F = 13.58, p < .001$ ). Finally, significant main effects were found for ceiling

height ( $F = 243.00, p < .001$ ), enclosure ( $F = 61.21, p < .001$ ), and curvature ( $F = 232.83, p < .001$ ) on PC3 (*fascination*).

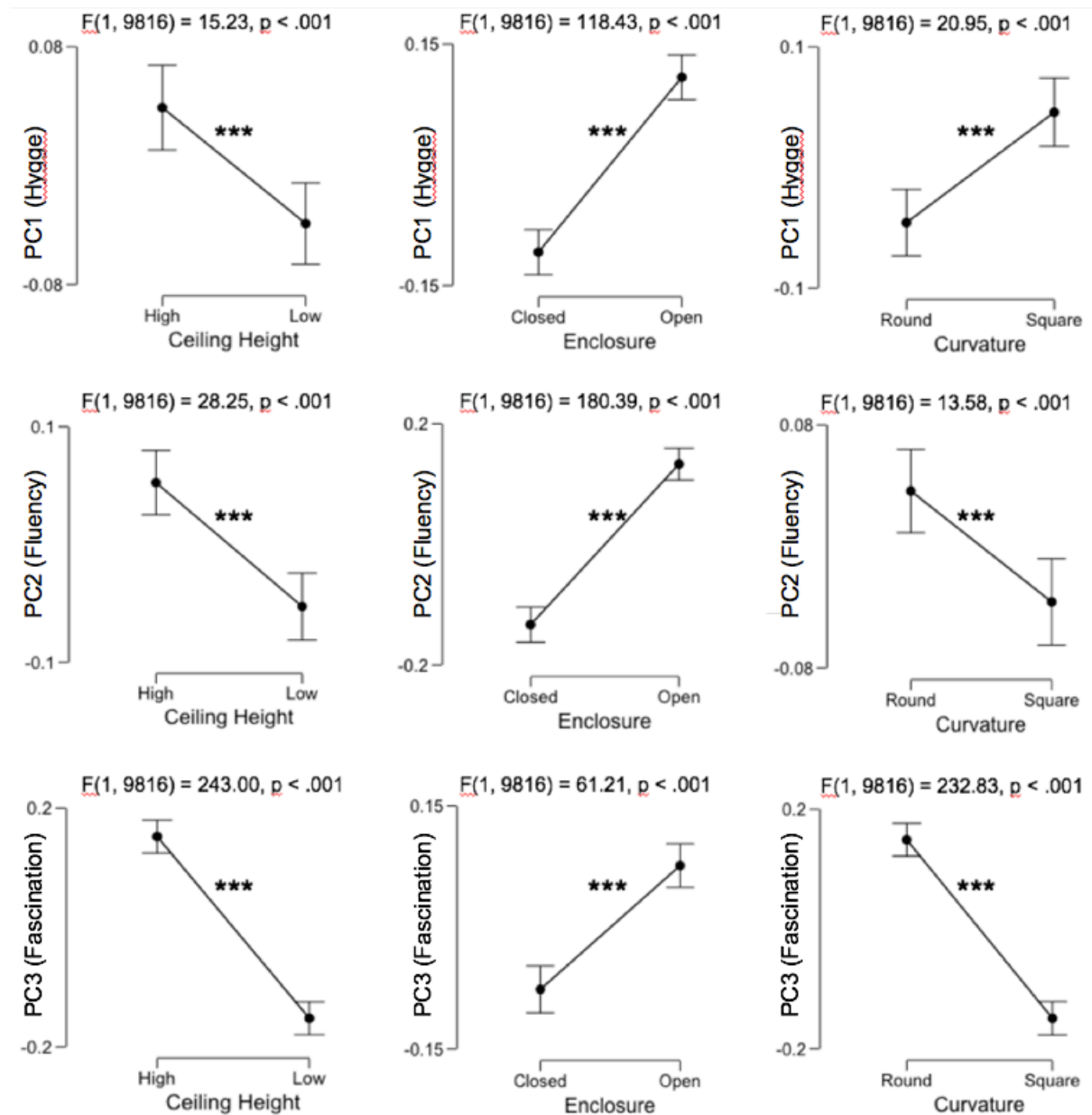


Figure 3.8: 3-way factorial ANOVA results and plots of principal component scores as a function of architectural variables. Error bars represent 95% confidence intervals of PC scores for each condition.<sup>26</sup>

<sup>26</sup> Plots created using JASP statistical software (Wagenmakers, 2016).

## Discussion

This study set out to answer two questions. First, do latent psychological constructs underlie visual responses to interior architectural scenes? Second, do basic design features of ceiling height, enclosure, and curvature modulate these psychological constructs? In Experiment 1, PCA revealed that three principal components - *fluency*, *hygge*, and *fascination* - collectively explained 90% of the variance across a wide variety of response measures. PCA in the replication study yielded a similar factor structure that explained 76% of the variance in the data. ANOVA results from Experiment 1 showed that images depicting open spaces received significantly higher scores on *fluency*, *hygge*, and *fascination* than enclosed spaces. Curved interior scenes also yielded significantly higher *fascination* scores than rectilinear scenes, and scenes showing rooms with high ceilings likewise resulted in significantly higher *fascination* scores than those showing rooms with low ceilings. These same five findings were replicated in the ANOVA results of Experiment 2. Additionally, in the replication study, scenes with high ceilings received significantly higher scores on *fluency* and *hygge* than scenes with low ceilings, and rectilinear scenes scored significantly higher on the *hygge* component and lower on the *fluency* component than curvilinear scenes.

To elaborate on the PCA findings, the first principal component, *fluency*, accounted for 40% and 25% of the variance in image ratings for Experiments 1 and 2, respectively. Organization, beauty, valence, and approachability loaded on this component in both studies.<sup>27</sup> The close relationship between organization and these three global response measures is consistent with fluency theory, which argues that ordered arrangements of a scene's composition – including structural redundancy, balance, and symmetry – heighten aesthetic appeal by increasing the efficiency, or *fluency*, of information processing in the visual system (Arnheim, 1971; D. J. Graham & Redies, 2010; Oppenheimer & Frank, 2008; Palmer, Schloss, & Sammartino, 2013; Ramachandran & Hirstein, 1999; Reber et al., 2004). Previous empirical work has indeed demonstrated that order and related constructs are reliable predictors of aesthetic responses to visual art (Birkhoff, 1933; Eysenck, 1957; Oppenheimer & Frank, 2008; Palmer et al., 2013) and landscapes (R. Kaplan, 1973; R. Kaplan & Kaplan, 1989; S. Kaplan,

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<sup>27</sup> Four of the excluded measures – vitality, uplift, comfort, and relaxation – proved to be nearly redundant measures of valence in Experiment 1 and were therefore most closely associated with this first principal component.

1987). Environmental disorder, by contrast, has been linked to heightened anxiety (Tullett et al., 2015), increased rule-breaking behavior (Kotabe et al., 2016b), reduced cognitive performance (Evans, Gonnella, Marcynyszyn, Gentile, & Salpekar, 2005), and a diminished sense of meaning in life (Heintzelman & King, 2014). Building on these past findings, the results of the present study suggested that the *fluency* component was primarily driven by the perception of organization but also involved multiple domains of psychological processing, including cognitive, affective, and behavioral responses to architectural scenes.

The second principal component explained 27% and 30% of the variance in image ratings for Experiments 1 and 2, respectively. In both studies, three psychological measures converged on this component: personalness, hominess, and naturalness. All three of these measures align closely with Danish concept of *hygge*. Because these three *hygge*-related measures loaded most strongly on this component, *hygge* was chosen as the name for the component itself. The following paragraph offers further explanation of this Danish concept and how it relates to these three measures (personalness, hominess, and naturalness) that loaded on the component.<sup>28</sup>

*Hygge* is a Danish word that describes “a feeling of coziness, warmth, and togetherness” (Wiking, 2017, p. 25) that is often felt in the presence of intimate spaces and social settings. Wilson describes this feeling as being akin to “a sense of warmth, ease, cosiness, security, relaxation, familiarity” (J. Wilson, 2011). While the term is often used in Danish culture to describe a particular type of social atmosphere, it can also describe the feeling created by architectural spaces (Wiking, 2017). For instance, the word *hygge* might capture the feeling created by an intimate fireside conversation, but it could also be used to describe the warm ambiance of the living room in which that conversation takes place. The present discussion focuses on the spatial dimension of the word *hygge*, given that participants in the studies

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<sup>28</sup> Although the name *hygge* was chosen to describe this component, it is important to recognize that in any principal components analysis, the choice of names for individual principal components is subject to the experimenter's interpretations. The name itself is only a description of the component based on the variables that load on it. The name should not be interpreted as a literal or complete definition of the component. More than one component name can often be used to describe any given principal component (Jolliffe, 2011). In this case, *hygge* seemed to be an appropriate name choice given that the three variables which loaded on this component (personalness, naturalness and hominess) all describe different aspects of *hygge* as cited in the literature above. However, other possible component names could have been chosen to describe this component, including names like “warmth,” “coziness,” or “intimacy.” All of these alternative name choice, like *hygge*, have both social and environmental connotations.



viewed images of architectural spaces. Since there were no people depicted in the spaces, the social dimensions of *hygge* are not as relevant to this discussion. *Hygge* in the architectural sense is often associated with home environments and “has a strong relationship to the material arrangement and use of the home” (Bean, 2011). Environments that generate this mood generally feel “personal and authentic” (Linnet, 2012, p. 403) and “echo the feeling of home” (Wiking, 2017, p. 24). These descriptions of *hygge* align closely with two of the psychological dimensions that loaded on the second principal component: hominess and personalness. The spatial dimension of *hygge* nicely integrates these two qualities captured in the principal components analysis.

*Hygge* also relates closely to the concept of *wholeness*, which Alexander describes as an environmental quality that makes occupants feel more intimately connected to their surroundings and more liberated to express their authentic personalities (Alexander, 1977, 1979, 2002). Linnet writes about a similar phenomenon of “rooting,” or increased connectedness, that occurs in the presence of *hygge* (Linnet, 2012, p. 407). Similarly, Wilson articulates that *hygge* is associated with “a sense of belonging – belonging to one’s culture and belonging to one’s immediate environment” (J. Wilson, 2011). Like wholeness, *hygge* therefore has both socio-cultural and spatial connotations. Spaces that create *hyggelig*<sup>29</sup> atmospheres often feel “organic” and “not strongly controlled” (Linnet, 2012, p. 405), qualities that align with the measure of *naturalness* in this study. Wholeness has similarly been linked to natural visual patterns in architecture (Alexander, 2002) and to loose, organic construction processes (Alexander, 2004). Thus, the component name *hygge* also incorporates the third major variable that loaded on this component in the study, naturalness, in addition to the two variables described above, personalness and hominess. In summary, the experience of *hygge* may depend on interactions between sensory inputs (i.e., naturalistic stimuli) and affective processing mechanisms (i.e., feelings of belonging).

At first glance, one might conclude that it would be inappropriate to use *hygge* as a general description of a type of architectural experience given that this is a uniquely Danish concept. It is important to note, however, that although this concept has received particular emphasis

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<sup>29</sup> Translation: “*hygge-like*” (Wiking, 2017)

in Danish culture, *hygge* has close translations in many languages, including the Canadian *hominess*, the Dutch *Gezelligheid*, the Norwegian *koselig*, and the German *gemütlichkeit* (Linnet, 2012; Wiking, 2017). Indeed, Wilson writes that while “every society has an equivalent or approximation of the *hyggelig* experience, it seems that Danish society is perhaps the only one to frame this particular type of socio-spatial experience as a specific, primary feature of its cultural identity” (J. Wilson, 2011, p. 15). The emphasis on social and environmental *hygge* in Danish culture is widely considered a contributing factor to the country’s high levels of wellbeing (Wiking, 2017).

The third principal component from the PCA, *fascination*, explained 24% and 20% of the variance in image ratings in Experiments 1 and 2, respectively. In both studies, this component represented the vector sum of two variables, complexity and interest. In Experiment 1, explorability and stimulation also exhibited such high bivariate correlations with interest that they were considered redundant variables. The close relationships that emerged between these four measures are consistent with previous research. Interest ratings of visual art have been shown to correlate closely with stimulus complexity (Daniel E. Berlyne, 1971; Silvia, 2005, 2012). Complexity has also been found to predict stimulation responses to both art and architectural images (Daniel E. Berlyne, 1970, 1971; Heath, Smith, & Lim, 2000; Taylor et al., 2005). In response to the widespread proliferation of minimalism in post-war Western architecture, several architectural theorists emphasized the importance of visual complexity and ornament for generating interest and excitement in the built environment (Alexander, 2002; Salingaros, 2007; Venturi et al., 1977). Kaplan and Kaplan (1989) proposed that complex landscapes provide a richness of information that triggers visual interest and motivates exploration. Early studies in empirical aesthetics also revealed close associations among these four response measures (D. E. Berlyne, 1963; Day, 1967). The results here extend these past findings to the built environment by demonstrating that complexity, interest, stimulation, and exploration all loaded on one multi-modal dimension of psychological experience in response to architectural scenes.

The three-part factor structure that emerged from these studies on images of architectural interiors builds on the pivotal psychological framework that Kaplan and Kaplan (1989) proposed for outdoor environments. Their seminal “preference matrix” outlined two psychological dimensions that contribute to aesthetic preference for outdoor landscapes:

*understanding* and *exploration*. *Understanding*, which describes “the need to make sense of what is going on” (R. Kaplan & Kaplan, 1989, p. 51) in a landscape, is influenced by environmental features such as coherence (how ordered a scene looks) and legibility (how easily a scene can be recognized, interpreted, and remembered). This psychological dimension aligns closely with the *fluency* component of this study, which describes how easily information in an architectural scene can be processed. The Kaplans’ *exploration* dimension encompasses the human desire to “find out more about what is going on in one’s surroundings” (R. Kaplan & Kaplan, 1989, p. 51). According to their model, environmental features that stimulate exploration include complexity (the informational richness of a scene) and mystery (the promise of hidden information waiting to be revealed). This dimension echoes the component described here as *fascination*, a term that S. Kaplan later adopted in his research on Attention Restoration Theory (Berman et al., 2008; S. Kaplan, 1995; S. Kaplan & Berman, 2010).<sup>30</sup>

Intriguingly, the Kaplans’ framework for landscape aesthetics offers no equivalent to the *hygge* component, suggesting that this dimension of psychological experience may be specifically activated in response to architectural scenes. Perhaps owing to the widespread influence of the Kaplans’ work, psychological measures related to *fluency* (e.g. coherence, order) and *fascination* (e.g. complexity, interest) have been widely studied in environmental psychology research. *Hygge* and related constructs (e.g. hominess, personalness, coziness) have received much less attention in empirical research. One reason for this gap in the literature may be that the majority of environmental psychology research to date, including much of the Kaplans’ work, has focused on outdoor rather than interior environments. Given that *hygge* has historically been applied more often to descriptions of home environments and interior spaces (Linnet, 2012; Wiking, 2017), it seems logical that this concept would not feature as prominently in research on exterior environments. Another possible explanation for the relative lack of *hygge*-related research may stem from divergent cultural values. While *hygge* is an important part of Danish culture and identity (Wiking, 2017), the proxies for these

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<sup>30</sup> According to Attention Restoration Theory (ART), environments that are inherently *fascinating* are restorative, because they capture involuntary attention in an automatic, bottom-up fashion and allow directed attention mechanisms, which are controlled in top-down fashion, a chance to replenish (Berman, Jonides, & Kaplan, 2008; S. Kaplan, 1995).

terms in English (e.g. hominess, coziness) are not as integral to the cultural identities of the English-speaking cultures of the West. Therefore, environmental psychologists based in non-Danish countries may be less likely to initiate research on this topic. However, the increased focus on *hygge*-related concepts in recent architectural literature (Alexander, 2002; Wilson, 2011) and in American popular culture (Newman, 2017; Wiking, 2017) indicates that the idea of *hygge* may resonate with people far beyond the borders of Denmark, and that it may therefore be a topic worthy of further investigation.

Our PCA results suggest that the experiences of *fluency*, *hygge*, and *fascination* all depend on multiple domains of psychological processing, indicating that the most salient psychological responses to architectural scenes are likely generated by the integration of cognitive, emotional, and sensory information. Furthermore, in both experiments, beauty, valence, and approachability loaded moderately on all three principal components. This finding suggests that the most global measures of visual responses to architectural scenes (how beautiful a room looks, for instance) may be influenced by all three of these underlying psychological constructs. The near orthogonality of order and complexity in the two PCA studies also supports previous theoretical claims that order and complexity are consistently perceived as independent dimensions of the physical environment (Alexander, 2002; R. Kaplan & Kaplan, 1989; Salingaros, 2007). Complex spaces, for instance, are not necessarily perceived as disordered, if the arrangement of complex parts forms a coherent whole. This is an important finding because it suggests that order and complexity may be perceptually-salient qualities of the built environment that can be manipulated independently in architectural design.

The ANOVA results suggested that spatial enclosure had the strongest impact on psychological responses. In both experiments, scenes depicting open spaces received significantly higher scores than scenes depicting enclosed spaces on all three principal components, thus replicating past findings that images of open architectural environments are often perceived as more beautiful (Vartanian et al., 2015), safer (Stamps, 2005; Fich et al., 2014), and more likely to stimulate movement and exploration (Vartanian et al., 2015). These results also support Appleton's theory that humans prefer environmental scenes with greater affordances of visual prospect (Appleton, 1975) and Hildebrand's hypothesis that evolved landscape preferences extend to the built environment (Hildebrand, 1999; Vartanian et al., 2013). Furthermore, these results suggest that previously reported aesthetic preferences for

high ceilings and curved structural forms may be driven by sensory experiences related to visual interest, simulation, and exploration. These hypotheses are consistent with past fMRI findings that architectural scenes depicting rooms with high ceilings and curved geometry differentially activated neural structural associated with visuospatial exploration and attention (Vartanian et al., 2015).

The ANOVA also yielded some unexpected results. It was surprising to find that scenes showing open spaces and high ceilings were significantly associated with higher *hygge* scores. Since this psychological construct is typically associated with feelings of “cozy interiority” and with spaces that create “a strong sense of being inside” (Linnet, 2012), images depicting enclosed rooms with low ceilings were expected to score highest on this component. However, many environmental variables contribute to a *hyggeligt* ambiance, including lighting, surface textures, color, and furniture arrangement (Linnet, 2012; Wiking, 2017). Since these other variables were not controlled for in the stimuli, it is possible that they confounded the ANOVA results by influencing ratings above and beyond the effects of enclosure and ceiling height. Future researchers interested in the architectural correlates of *hygge* might benefit from using more comprehensive measures of the built environment, such as the image statistics outlined in Chapter 5.

## Limitations

Images of buildings were used as stimuli for this study in order to expose participants to a wide variety of architectural scenes within a reasonable timeframe. However, the use of two-dimensional images may limit the generalizability of these findings to three-dimensional built spaces. Not only do two-dimensional scenes lack the depth cues of real spaces, but they also fail to capture the temporal dimension of architectural experiences, such as the dynamic environmental changes a person experiences while navigating through a building, by artificially freezing a particular vantage point in time. Future experiments could leverage real buildings or immersive technologies like virtual reality to answer similar questions using more life-like simulations of architectural environments. This study also focused on purely visual aspects of psychological responses to architecture. In doing so, no inferences could be made about the contribution of nonvisual senses to architectural experiences, which are likely substantial and could potentially influence or interact with visual experiences in the built

environment. Finally, the images used in these experiments were counterbalanced on only three basic architectural design variables, which together capture a very limited proportion of variance in visual properties of an architectural scene. These variables were included in this experiment because they are among the few features that have previously been shown to correlate significantly with psychological and neural responses to architectural scenes (Vartanian et al., 2013, 2015).<sup>31</sup> However, they are quite rudimentary measures that fail to capture the visual complexity of many architectural spaces. The next chapter uses image statistics to measure more nuanced architectural parameters like scaling patterns and color distribution, which may have a more significant impact on a person's psychological experience when viewing an architectural scene.

### Conclusion

This chapter investigated the primary psychological dimensions of visual responses to architectural scenes. A pair of studies identified three latent psychological constructs – *fluency*, *fascination*, and *hygge* – that collectively explained the majority of variance across a range of psychological response measures and design features. The first two components align closely with the psychological dimensions outlined in the Kaplans' pivotal "preference matrix" of landscape aesthetics (R. Kaplan & Kaplan, 1989). Indeed, *fluency* and *fascination* are well-established dimensions in assessing natural scenes and visual art. *Hygge*, however, emerged as a new dimension in relation to interior architectural scenes that has received scant attention to date in empirical research.

These studies represent an exploratory effort to understand how visual qualities of architectural design can impact subjective human experience, using empirical research methods of psychology. This chapter makes no claims that these three principle components account for all aspects of psychological experiences in the built environment. Rather, they provide a simple framework that seems useful for research and environmental design. A potential application of this work could be to design a system for rating the psychological impact of buildings using the three principal components identified in this study. For instance,

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<sup>31</sup> This is probably not because they are the most psychologically salient architectural variables, but rather due to the fact that there has been very limited research to date on the psychology or neuroscience of architecture.

buildings could be mapped onto a three-dimensional coordinate system, with each principal component representing one orthogonal axis of the graph. Architects could use similar rating scales to predict the experiential impact of design iterations before buildings are constructed. This three-component framework also provides a useful model for future researchers interested in testing how design features of real or virtual environments impact occupants' psychological experiences. This study therefore represents a small step towards leveraging cognitive science to improve the environments that surround us for most of our lives.

# **Chapter 4:**

## **Natural patterns in architecture**

### **Introduction**

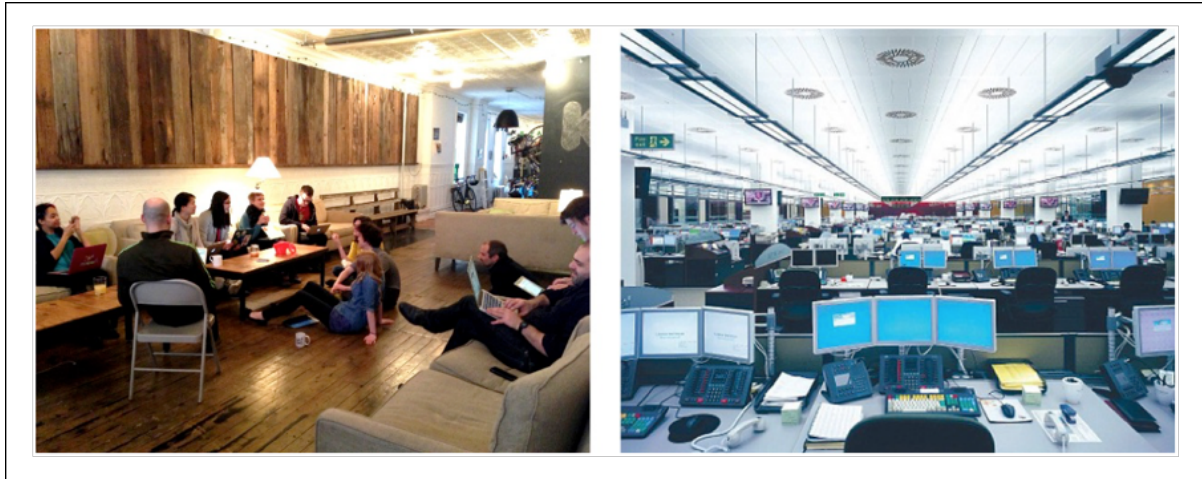
The previous two chapters explored the neural networks and psychological dimensions associated with architectural experience. Here, the focus shifts from “measuring the brain” to “measuring the environment.” Although rudimentary measures of the built environment were considered in Chapter 3 (Ceiling Height, Enclosure, and Curvature), these variables offered only a limited account of the diverse sensory qualities present in architectural spaces. The final two chapters of this thesis focus on identifying empirical measures that capture more holistic aesthetic properties of the built environment.

This chapter investigates two aesthetic qualities of the built environment that have previously been linked to positive psychological experiences: *adaptability* and *naturalness*. Both of these qualities are closely associated with Christopher Alexander’s theory of natural structure (Alexander, 2002). According to this theory, buildings develop nature-like visual patterns in their structure when the methods by which they are constructed resemble the adaptive processes of biological growth. These nature-like construction processes and patterns have been predicted to promote wellbeing in the built environment. This chapter provides a conceptual introduction to Alexander’s theory of natural structure and discusses the proposed influence of natural patterns on human flourishing.

### **Adaptability and naturalness**

Two environmental qualities are highlighted below that have been consistently linked to wellbeing across many cultures and environments: *adaptability* and *naturalness*. *Adaptability* describes an environment’s capacity to be adapted to the needs of its occupants. Thermal comfort researchers have found that human comfort in a building is more related to the amount of control occupants have over internal environmental conditions than to any particular temperature or humidity range (Nicol & Humphreys, 2002). Architectural features and organizational policies which allow occupants to control their local microclimate, including the provision of fans, operable windows, and the ability to move to different areas of the building, are termed “adaptive opportunities” (Baker & Standeven, 1995).





**Figure 4.1: (Left) Adaptable office (Kickstarter, 2013). (Right) Rigid, inflexible office (Milton, 2011).**

Office design researchers have found that workers tend to be more focused and productive when they are enabled to control their physical environments by moving the furniture, adjusting lighting, and personalizing their surroundings with decorations reflecting their personal and organizational identity (Haslam & Knight, 2010; Myerson, 2014). Figure 4.1 (Left) illustrates an adaptable office space with adjustable lighting, mobile furniture, and a variety of seating options. Figure 4.1 (Right), by contrast, shows a more rigid, inflexible office with identical furniture and homogenous overhead lighting. Participative office renovations that involve employees in the design process are often regarded as more successful than top-down planning approaches (Sundstrom & Sundstrom, 1986; Vischer, 2003). In healthcare environments, adaptive opportunities related to temperature, ventilation, acoustics, visual privacy, and lighting can significantly impact patient comfort, anxiety, circadian rhythms, and physiological health (Payne et al., 2014; Ulrich, Joseph, Choudhary, Zimring, & Quan, 2004). Environmental control in the home and surrounding vicinity enables occupants to personalize their surroundings to fit their own functional needs and also affects how people regulate social interaction with neighbors (Coburn, 2013; Gehl, 2011; Williams, 2005). Indeed, perceived lack of control over one's residential environment is a strong environmental predictor of stress and anxiety (Baum, Singer, & Baum, 1981; Dunn & Hayes, 2000; Gove, 1979; Griffin, Fuhrer, Stansfeld, & Marmot, 2002; Hatfield et al., 2002; Shenassa, Daskalakis, Liebhaber, Braubach, & Brown, 2007). For instance, loss of control over social interaction and cumulative instances of unwanted contact have been found to predict stress and social withdrawal behaviors (Baum & Valins, 1977).

The human need for environmental adaptability is a manifestation of the eudaimonic principle of autonomy, or self-determination (Ryff & Keyes, 1995). Self-motivated behaviors that are adapted to one's unique interests, skills, and goals tend to be more rewarding than externally-imposed, generic activities (Nix et al., 1999; Ryan & Deci, 2000). Built environments, in turn, are more efficient when they can be physically adapted to fit occupants' unique functional needs than when they are rigidly designed around preconceived generic behaviors (Alexander, 2004). In short, environmental adaptability allows people to pursue autonomous behaviors more effectively and to experience greater freedom to flourish (Alexander, 2004; Nicol & Humphreys, 2002; Ryan & Deci, 2000).

Strong evidence has also emerged linking positive health to a second environmental quality, *naturalness*. Studies indicate that exposure to nature supports all three dimensions of wellbeing: positive emotions, healthy behaviors, and psychological resources. Natural environments and urban green spaces have been consistently linked to better mood (Barton & Pretty, 2010; Bowler, Buyung-Ali, Knight, & Pullin, 2010; Bratman, Daily, et al., 2015; K. Korpela et al., 2014), more frequent walking and exercise (Pretty et al., 2005), increased social interaction (Zhang et al., 2014), and pro-social tendencies (Mayer & Frantz, 2004), stronger friendship networks (Kweon et al., 1998), increased trust and generosity (Zhang et al., 2014), mindful engagement and focus (Berto, 2005; Bratman, Daily, et al., 2015; Howell, Dopko, Passmore, & Buro, 2011; S. Kaplan, 1995; Tennessen & Cimprich, 1995), improved working memory performance (Bratman, Daily, et al., 2015), self-esteem (Barton & Pretty, 2010; Pretty et al., 2005), and increased subjective vitality (Ryan et al., 2010).

For instance, one robust longitudinal experiment found that the frequency of use of green outdoor common spaces in residential communities of older adults (n = 91) significantly predicted the strength of neighborhood social ties (i.e., friendship networks) and the sense of community reported by residents (Kweon et al., 1998). In another series of laboratory experiments, participants who were exposed to more beautiful images of nature exhibited significantly more generous and trusting behaviors than those who were exposed to less beautiful images of nature. Likewise, participants exposed to more beautiful images of nature demonstrated a higher incidence of helping behaviors than a control group (Zhang et al., 2014). These results suggest that exposure to nature, particularly beautiful nature, can yield important prosocial benefits.



**Figure 4.2: The salutary natural landscape of the Scottish Highlands (SummitPost, 2010).**

The evidence that has emerged from this body of literature supports Edward O. Wilson's classic "biophilia hypothesis," which states that humans have an "innate tendency to focus on life and life-like processes" (E. O. Wilson, 1984, p. 1). Psychologist Eric Fromm first introduced the concept of biophilia to describe humans' psychological orientation towards all that is alive and vital (Fromm, 1980). Expanding on Fromm's definition, Wilson argues that people have a biological need to associate with the natural environment and particularly with "living" organisms and natural systems (E. O. Wilson, 1984). This fundamental need, he contends, has developed throughout our species' evolutionary heritage. According to this theory, humans are quite literally dependent on living systems, not only for physical sustenance but also to fulfill "the human craving for aesthetic, intellectual, cognitive, and even spiritual meaning and satisfaction" (E. O. Wilson & Kellert, 1995, p. 20). Wilson writes that nature plays an essential role in human cognitive development, social bonding, physical healing, emotional restoration, and a number of other processes critical to wellbeing (E. O. Wilson & Kellert, 1995). He also questions the psychological ramifications of living in "the artificial new environments into which technology has catapulted humanity" (E. O. Wilson, 1984, p. 32), which lack the health-sustaining features of natural systems.

Some have questioned this sharp natural vs. man-made dichotomy in Wilson's work. Many iconic landscapes that we consider natural have actually been heavily shaped by human intervention. Most of England's proverbial "green and pleasant land" is actually deforested and heavily re-shaped monoculture farmland. Until recently, the magnificent Scottish Highlands were blanketed by the biodiverse Caledonian forest and owe their present aesthetic to several centuries of shipbuilding and sheep breeding (Hughes & Duchaine, 2012). Yet many regard these man-shaped environments as beautiful, restorative, and healthy places. Likewise, one could argue that humans, as natural organisms, are capable of creating natural places. If we regard inorganic structures built by other species, like beehives, birds' nests, and beavers' dams, as products of nature, then could we not also define early cave-

dwellings and houses constructed by our ancestors, or even some infrastructure that we still build today, as “natural” places? If so, what constitutes an “artificial” environment, and when did our buildings start to take on that quality? Wilson’s key terms – living, life-like, man-made, and artificial – require further clarification.



**Figure 4.3: (Left) "Man-made" natural environment (Johnson, 2013). (Right) "Natural" man-made environment (North, 2008).**

The biophilia hypothesis also fails to address the broad spectrum of environmental quality present in human infrastructure and undersells the potential for well-designed man-made places to support human life and health. Research indicates that “a well-designed and attractive urban environment,” even when devoid of biological life, “can have a stress-reducing and mood-enhancing power equal to that of an attractive natural environment” (Karmanov & Hamel, 2008, p. 115). The biophilia hypothesis offers little explanation for the spectrum of quality that people perceive in the inorganic built environment and the associated health outcomes that often align with that spectrum (Pretty et al., 2005; Zhang et al., 2014). As one scholar writes, “we should move beyond a nature-urban dichotomy and concentrate on how to successfully merge natural and urban elements to promote human health and wellbeing” (Kytä & Broberg, 2014, p. 648).



Figure 4.4: (Left) "Unattractive urban" (Brownsville, 2008). (Right) "Attractive urban" (Dijstelberge & Harskamp, 2013).

## The theory of natural structure

In *The Nature of Order* book series (Alexander, 2002), architect Christopher Alexander proposes a new definition of environmental quality that applies to both natural and man-made environments. These books help explain why the environmental qualities of *naturalness* and *adaptability* are so important for human wellbeing. Using a systems approach, Alexander identifies fifteen fundamental geometric properties that are present in the structure of many natural (including biological) systems and outlines the processes of adaptive growth by which these organizational patterns are generated. His theory proposes that man-made environments also embody these fifteen properties to varying degrees, depending on the extent to which their construction method follows growth-like generative processes. According to this view, buildings exhibiting a higher presence of the fifteen properties can be said to approach the organizational structure of living systems in nature, which are referred to here as *natural structure*.<sup>32</sup> Alexander argues that the geometric organization of natural structure embodies a high degree of order and functionality, and that built environments embodying this type of order may be most supportive of human life and wellbeing.

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<sup>32</sup> This concept is often referred to as "living structure" in Alexander's work (Alexander, 2002). However, the term "natural structure" is adopted here because it more consistent with the language used in related research in environmental psychology and biophilic design.

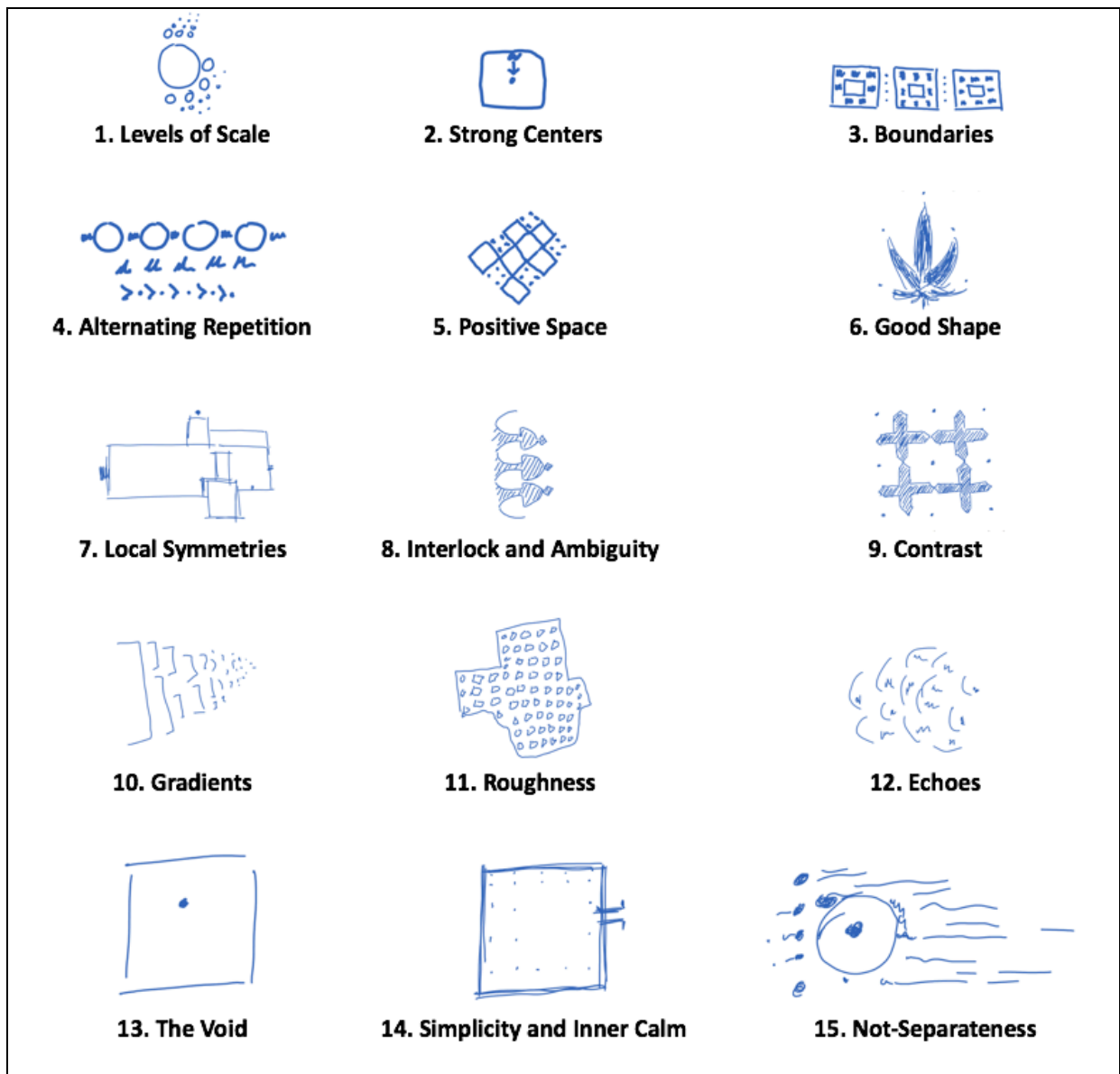


### **Natural vs. artificial structure**

Many natural systems, Alexander writes, share fifteen emergent geometric properties. These patterns of natural structure are listed in Figure 4.5. A brief summary of each pattern is given below. In the subsequent overview, three of the properties (*Boundaries*, *Levels of Scale*, and *Local Symmetries*) are described in greater detail in order to give the reader a more nuanced visual understanding of some of these patterns and to elucidate their functional implications in nature and in architecture. These three specific patterns were chosen for in-depth description because they are among of the most straightforward patterns to understand. A full description of all fifteen patterns is beyond the scope of the research questions of this thesis. The lengthy discussion needed to describe them in full would distract from these research questions. However, an interested reader can find complete descriptions of all the patterns in Alexander (2002).

*Overview of the fifteen patterns*

**Figure 4.5: Fifteen patterns of natural structure (Alexander, 2002).**



The diagrams illustrated in Figure 4.5 provide schematic examples of each of the fifteen proposed patterns of natural structure. Alexander describes many of these patterns using the concept of ‘Centers,’ which is a somewhat nuanced idea outlined in detail in Alexander, 2002 (pp. 80-102, 151-157). A basic definition of a Center is any field of physical space (architectural or non-architectural) that exhibits a more ordered geometric structure relative to the space around it. Many of the fifteen patterns are described as higher-level arrangements of Centers, and these arrangements can occur in architectural structure as well as in any other type of object or region of physical space (e.g. cells, trees, rugs, paintings, mountains).

When objects (including buildings) exhibit the Levels of Scale pattern, “the centers these objects are made of tend to have a beautiful range of sizes, and...these sizes exist at a series of well-marked levels, with definite jumps between them. In short, there are big centers, middle-sized centers, small centers, and very small centers ” (Alexander, 2002, p. 145). The Strong Centers pattern describes the existence of coherently organized sets of points in space that form “a local zone of relative centeredness with respect to the other parts of space” (Alexander, 2002, p. 84). The third pattern, Boundaries, refers to zones of space that surround strong centers; these boundaries serve to “keep this center distinct and separate from the world beyond it, and yet also have the capacity of uniting that center with the world beyond the boundary” (Alexander, 2002, p. 159).

Alternating Repetition describes spaces “where the rhythm of the centers that repeat is underlined, and intensified, by an alternating rhythm interlocked with the first and where a second system of centers also repeats, in parallel” (Alexander, 2002, p. 166). The Positive Space pattern “occurs when every bit of space swells outward, is substantial in itself, is never the leftover from an adjacent shape” (Alexander, 2002, p. 173). Good Shape is described as “a center which is made up of powerful intense centers, which have good shape themselves...in most cases, the good shape, no matter how complex, is built up from the simplest elementary figures” (Alexander, 2002, p. 181). Local Symmetries refers to the presence of symmetrical small-scale centers within a building, and the absence of global symmetry of the whole building.

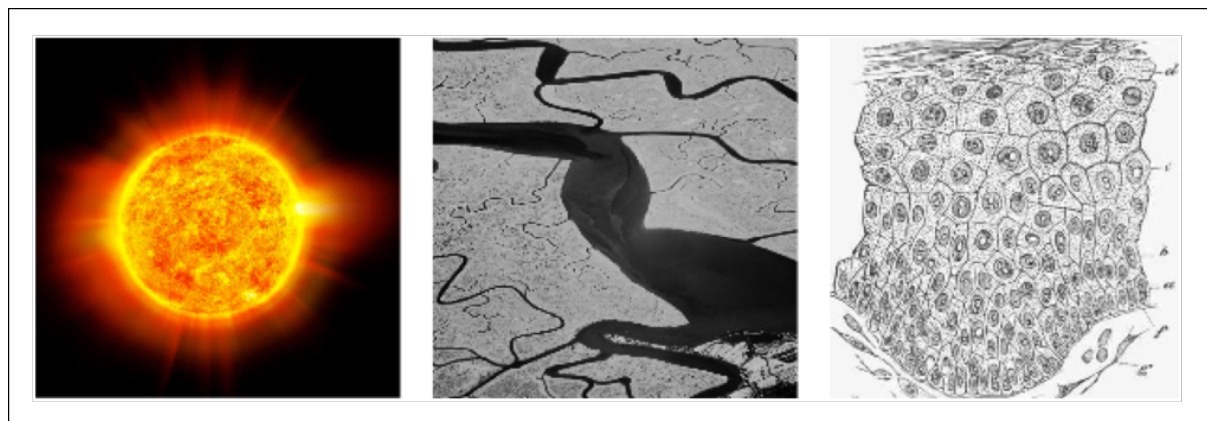
The eight pattern, Deep Interlock and Ambiguity, is closely related to the Alternating Repetition pattern. Deep Interlock and Ambiguity describes the connection of one set of centers to another set of centers via a third set of centers that ambiguously belong to both. Contrast refers to the presence of centers that display a sharp distinction between their own character and the character of surrounding centers. The Gradients pattern exists when there are adjacent centers in a field of space that gradually vary in size, spacing, intensity, and character. Roughness describes the way in which centers draw their strength from irregularities in the size, shape, and arrangements of nearby centers; the opposite of Roughness is rote standardization and repetition of parts, which does not frequently occur in nature.



The twelfth pattern, Echoes, refers to a quality by which everything in a given field of space seems to be related, by virtue of a deep underlying similarity between shapes, angles, textures, and materials of parts. The Void describes the existence of a still place at the heart of a field of centers; the Void provides “the quiet that draws the center’s energy to itself, gives it the basis of its strength” (Alexander, 2002, p. 225). Simplicity and Inner Calm refers to the importance of reducing the number of centers in a field in order to strengthen the relative strength of each center. This pattern also emphasizes the value of geometric similarity and coherence within a structure. The final pattern, Not-Separateness, describes a quality of connectedness between a building and its surroundings, or between any center and the field of space around it; the center (or building) should be merged smoothly and sometimes indistinguishably with the environment around it. These fifteen patterns, Alexander observes, are important structural characteristics of most natural systems that contribute to both their function and their beauty.

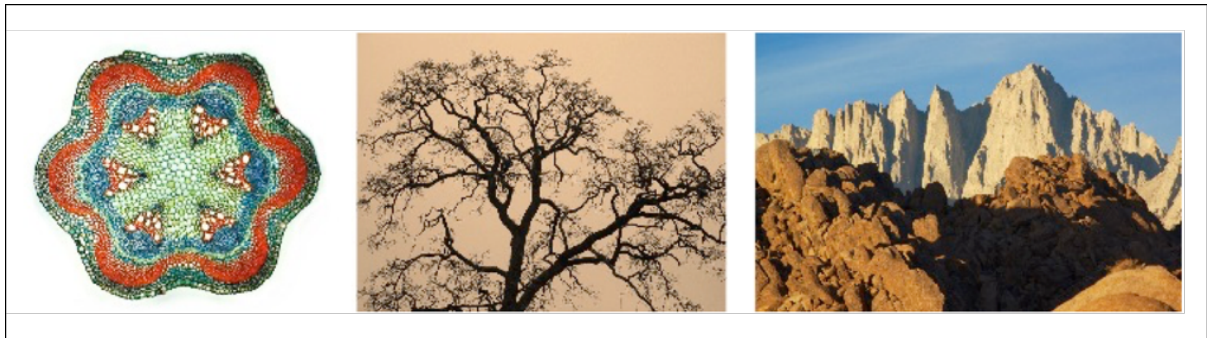
### *Examples of Boundaries, Levels of Scale, and Local Symmetries*

*Boundaries* (Figure 4.6): Natural systems tend to form thick external transitional layers, or zones of interaction, that both enclose and protect the systems and also connect them to the surrounding environment. The volume of a natural boundary tends to be on the same scale as, or larger than, the volume of the system being bounded. Examples include the corona of the sun, a boundary formed by nuclear and plasma processes; the buildup of river banks, a boundary created by the gradual deposition of sediments during stream flow; and mammalian cell boundaries formed by the cytological process (Alexander, 2004). Each of these boundaries serves a highly functional purpose for the system in which it is present.



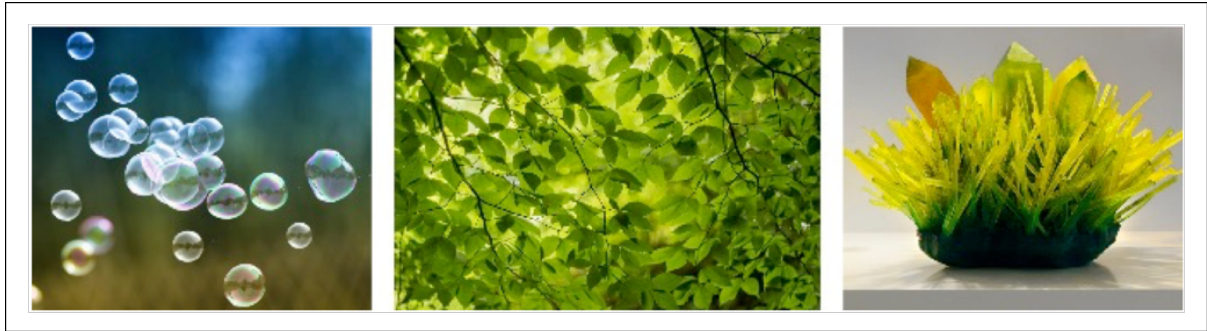
**Figure 4.6: Thick boundaries in natural systems at three different scales (Sapien, 2017; Yeo, 2016).**

*Levels of scale* (Figure 4.7): Natural systems usually exhibit a series of well-marked scales with definite jumps between them (Alexander, 2002). Any given component is rarely more than ten times larger than the equivalent structural component at the next-smallest scale. Mathematician Nikos Salingaros has observed that the smallest scales tend to be connected to the largest scales through a linked hierarchy of intermediate scales that gradually increase at a ratio of approximately 2.7:1, or the mathematical constant  $e$  (Salingaros, 2007). These scales provide structural and functional cohesiveness throughout natural systems (Alexander, 2004).



**Figure 4.7:** Many gradual *Levels of Scale* in a plant stem (Block, 2015), in the branches of a tree (Silvergreen, 2018), and in a mountain range (Keesaw, 2016).

*Local symmetries* (Figure 4.8): Small-scale geometric symmetries – including reflectional, rotational, translational, and other types of symmetry – tend to be highly concentrated throughout natural systems. Smaller parts often arrange themselves evenly in locally symmetrical groups, unless there are particular forces making them uneven (Alexander, 2002, p. 267). These small-scale symmetries, however, rarely add up to produce overall symmetry in the whole system. Highly organized systems, like biological organisms, are usually packed with dense local symmetries, but few are perfectly symmetrical on the whole (Alexander, 2002).



**Figure 4.8:** Local symmetries in soap bubbles (Danger, 2014), tree leaves (Cromer, 2015), and crystal growth (Fox, 2013).

The fifteen properties, including the three described above, are not only present in biological systems but also in many types of organic and inorganic systems throughout nature. They also appear, to varying degrees, in the built environment, at all scales (Alexander, 2002). In buildings, as in nature, these properties often serve key functional purposes. A few architectural examples of each are discussed below.

*Boundaries:* The Victorian house on the left in Figure 4.9 has a substantial exterior boundary comprised of a wrap-around porch and layers of bushes, grass, and trees. This boundary encompasses a larger volume of space than the house itself and serves as a functional transitional zone that encloses and protects the house while uniting the building with the surrounding environment. This zone also offers occupants a range of spatial uses and experiences between the private, indoor house and the public, outdoor street. These might include reading on the porch in the rain, throwing a Frisbee on the grass, or sitting and chatting on the front steps. The house on the right, on the other hand, features a jarring, abrupt transition from interior and exterior and does not provide a semiprivate boundary in which outdoor activities could take place. Boundaries improve architectural function at many scales; in door frames, for example, they strengthen the structural integrity of the wall membrane at a threshold of significant friction and vibration (Figure 4.10).



**Figure 4.9: (Left) House with substantial boundaries (Etsung, 2018). (Right) House with minimal boundaries (Cody, 2011).**



**Figure 4.10: (Left) Thick door boundary, strong door frame. (Right) Thin door boundary, weaker door frame.**

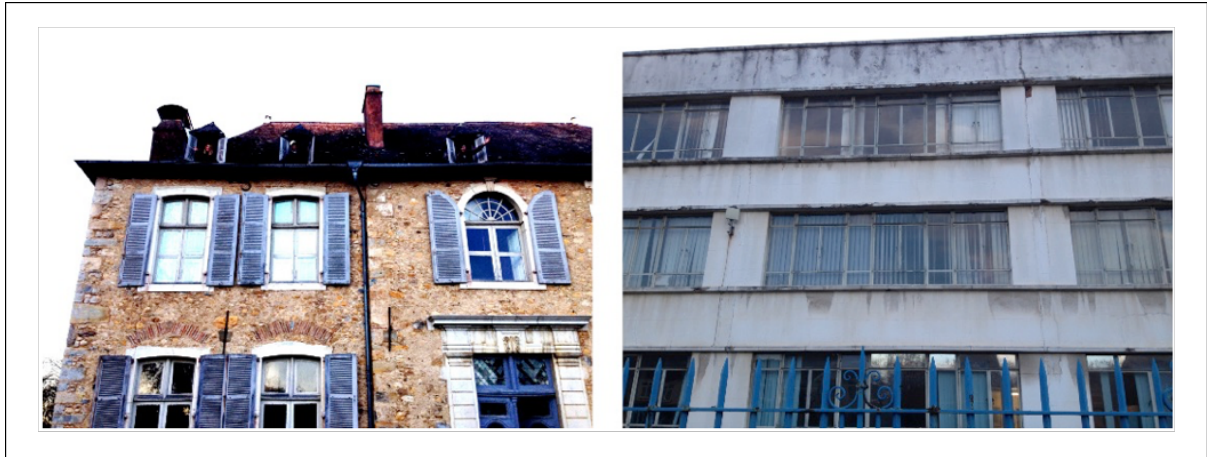
*Levels of scale:* At St. Mark's Basilica in Venice, shown on the left in Figure 4.13, the layering of arches within coherent *Levels of Scale* creates a clear and powerful main entrance that is simultaneously awing and welcoming. The front entrance to Le Corbusier's Ronchamp Chapel, by contrast, is difficult to identify, in part because there are few *Levels of Scale* working together to guide the eye to the main door, which instead gets lost in a puzzle of jumbled geometry.



In the 16<sup>th</sup>-century French chateau shown in Figure 4.12, *Levels of Scale* serve several functional purposes. Moving upwards from the large ground-floor windows to the small roof dormers, the window sizes gradually decrease in response to the increasing gradient of daylight that reaches the façade between the ground and the roof. Levels of scale are also evident in the sizes of stones comprising the exterior wall. The largest stones are reserved for the edge of the left façade, where two walls meet and the highest structural forces converge. The *Levels of Scale* in the Chateau's materials also enable the building to experience a "healthy" and resilient aging process. Natural weathering forces constantly move and re-shape all building materials, and the many integrated sizes of architectural components in this house enable its structure to shift and adapt slowly to these forces over time (Salingaros, 2007). Thus, the fractal geometry of weathering gets incorporated quite naturally into the façade. The 1960's school on the right, by contrast, features a rigid geometry lacking adaptable components or coherently ordered scales. As a result, natural processes have destroyed the structure after only a few decades, making it look more dilapidated and beaten than the much older building next to it.



**Figure 4.11: (Left) Many organized *Levels of Scale* at the entrance to St. Mark's Basilica, Venice. (Right) Fewer, and disorganized, *Levels of Scale* at the entrance to Le Corbusier's Notre Dame du Haut, Ronchamp (Dunham, 2011).**

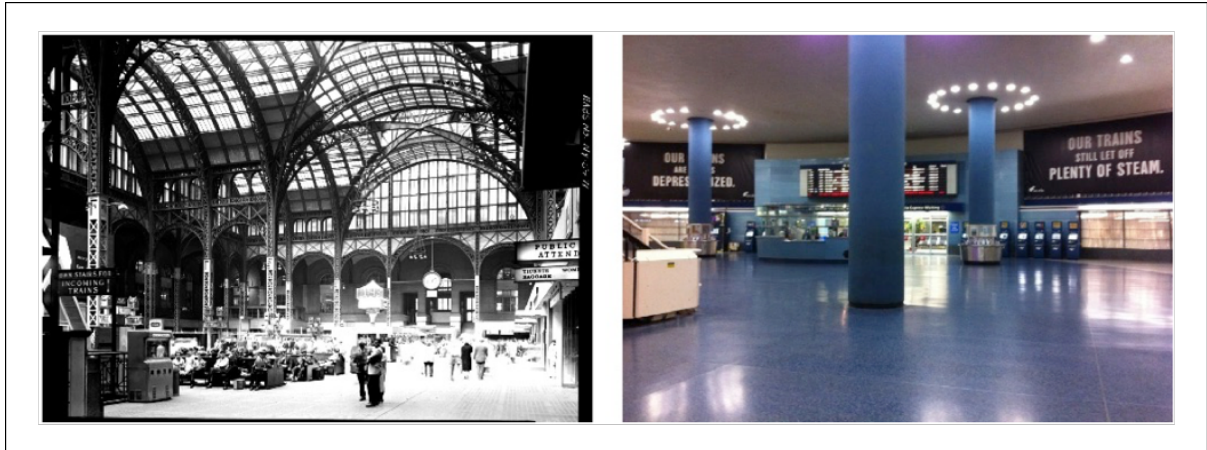


**Figure 4.12: (Left) Many ordered *Levels of Scale* in an aging 16th-century French chateau (Cardesse, France). (Right) Large jumps in scale, and no perceptible small-scale details, in a 20<sup>th</sup>-century school (Coventry, England).**

*Local symmetries:* The local symmetries in King's College Chapel (Figure 4.13, left) and old Penn Station (Figure 4.14, left) are essential to the structural integrity and spatial quality of the buildings. Both structures explode with fractal scaling of symmetrical arches, which disperse gravitational forces evenly from ground to roof and enable visitors to experience soaring, expansive clerestory windows and vaulting. Local symmetry has also been linked to ease of cognitive perception (Alexander & Carey, 1968). Coherent scaling of complex symmetries helped make the different spaces in old Penn Station more visually memorable, and thus easier for visitors to navigate, than the simplistic geometry of new Penn Station, where blank homogenous tunnels make it easier for travelers to get lost.



**Figure 4.13: (Left) King's College Chapel explodes with local symmetries (Sailko, 2011). (Right) Renzo Piano's chapel at Ronchamp has very few (Raftery, 2012).**



**Figure 4.14: (Left) The structure of Penn Station is a soaring web of local symmetries (Jaffe, 2013). (Right) New Penn Station's structure is bland, homogenous, and lacks organized visual information (NHRHS2010, 2007).**

Built environments in which these properties collectively emerge can be said to embody a certain degree of *natural structure* in that their geometric order resembles the organizational patterns of natural systems (Alexander, 2002). The buildings on the right in the adjacent photographs would be difficult to find in nature because they exhibit a type of structural organization quite alien to the sort of order found in natural systems. Instead, these shapes arise from idealized concepts of geometry that originated in the human mind, such as Euclidean geometry, which is derived from theoretical concepts of form like platonic solids (Fischler & Firschein, 1987). According to Einstein's theory of general relativity, however, physical space itself is non-Euclidean and can only be described by Euclidean geometry in exceptional conditions like low gravitational fields (Bussey, 1922). Architecture based on Euclidean form might therefore be described as "artificial" in that it physically manifests an intellectual concept of spatial order that does not occur when nature is left to its own devices.<sup>33</sup>

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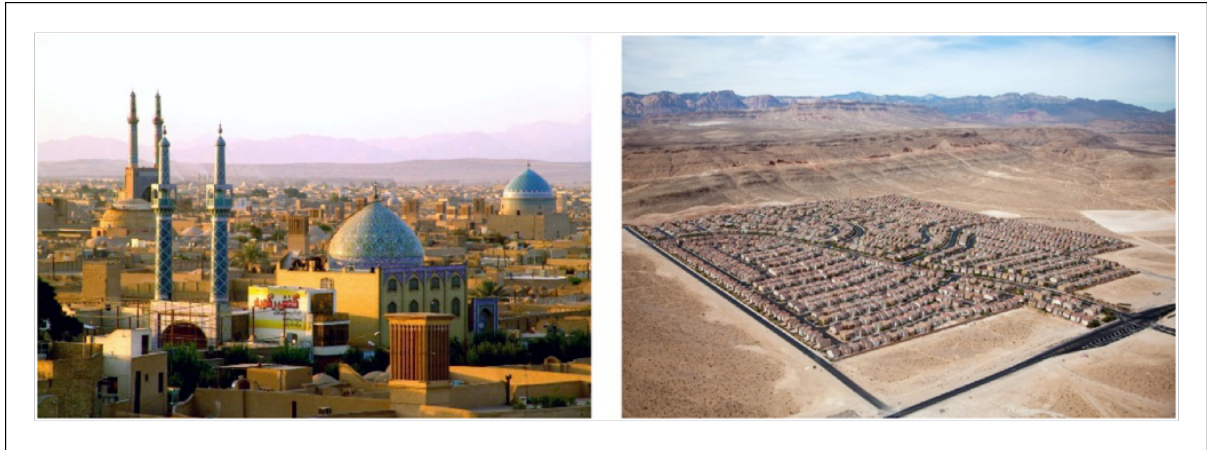
<sup>33</sup> Some scholars argue that the Second World War marked an important turning point in Western construction that led to an increased prevalence of Euclidean-based architectural forms (Alexander, 2002; Joye, 2007; Salingaros, 2007). Salingaros has argued that this aesthetic revolution was not entirely accidental, but was linked to an underlying motive of the Modernist architectural movement: to create shocking new forms that stood out in stark contrast from nature (Salingaros, 2007). This is a controversial view, however, that has not been widely accepted among architectural theorists.

### **Generated vs. fabricated structure**

According to Alexander (2004), natural and artificial structures not only diverge in form but also result from different types of construction processes. Wherever the fifteen geometric properties of natural structure appear in the built environment, they tend to emerge alongside each other, rather than independently, as the structural product of a generative and adaptive building process resembling natural growth. In this type of process, blueprints are not typically pre-planned in the top-down way that architects conventionally design buildings. Rather, buildings are generated according to local cultural rules and patterns that could be likened to the genetic codes carried in DNA. Buildings gradually “grow” or “unfold,” following these rules, through countless structure-preserving transformations (Alexander, 2004).

There is no rigid end-state in this approach. Rather, adaptive natural structures continue to evolve and adapt to their inhabitants and to their context, often according to the many small “design” decisions that the occupants themselves make over the course of months, years, and generations. Frequent user feedback molds the ever-evolving geometry of the building to support, at all times, the autonomous behaviors of its present group of occupants, and to function efficiently within the surrounding culture and environment. Building materials typically come from the local surroundings and are shaped on-site as the structure emerges, so that each component develops a unique geometry based on complex local spatial needs. Every part that is added to the growing structure is therefore adapted to its local human and environmental context so that it functions ideally within the emerging system. This is the type of process by which much of the world’s vernacular architecture has been generated (Alexander, 2004).





**Figure 4.15: (Left) Naturally generated desert development (Yazd, Iran). (Right) Artificially fabricated desert development (Las Vegas, USA) (MacLean, 2009).**

“Artificial” architecture, by contrast, is the product of top-down planning and fabrication. This method typically entails drawing up a complete, finalized design scheme, usually off-site, before construction begins, and then assembling the structure according to that rigid scheme with few changes or corrections along the way (Alexander, 2004). Once finalized, the inflexible design cannot be adapted to on-site feedback as the geometry of the building emerges in real time. The planned architectural structure conforms to the intellectual concepts of external planners, which often reflect Euclidean concepts of geometry and order. When this rigid process is taken to the extreme, the building inhabitants, who are uniquely aware of their own particular functional and spatial requirements, have little influence over the environments they occupy.<sup>34</sup>

A large-scale example of adaptive generation in the built environment can be seen the city of Yazd, Iran (Figure 4.15), which has naturally emerged from the desert landscape over the past 5,000 years. Throughout its growth process, the city has slowly unfolded based on many small architectural decisions made by thousands upon thousands of local inhabitants. Natural structure of this kind emerges gradually, often based on trial and error, so that generations of locals slowly develop collective understanding of which materials, geometries, and building

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<sup>34</sup> For a more in-depth review of the processes of natural generation and artificial fabrication, please refer to Alexander (2004), *The Process of Creating Life*

techniques function best for their local climate and culture.<sup>35</sup> At the other end of the spectrum, the development shown on the right in Las Vegas, Nevada, reflects the process of artificial fabrication. Here, generic Euclidean forms have been imposed on an incompatible landscape, based on the intellectual whims of a few totalitarian planners.



**Figure 4.16: (Left) Living room of Perry House, Williams College, USA. (Right) Living rooms of Seelye House, Amherst College, USA.**

This type of top-down planning can affect the environmental quality and functionality of the built environment at many scales. Figure 4.16 depicts two living rooms from student houses at rival colleges in the United States, Williams College (left) and Amherst College (right). These two houses were built within a decade of each other in the early 1900's with very similar spatial configurations and architectural styles. Williams has adopted a policy whereby current residents of each house select and arrange the furnishings for that particular building. Residents also participate in larger-scale structural renovation decisions (Briggs, Coburn, & Zheutlin, 2011). Amherst College, on the other hand, takes a top-down approach. Most furnishings, from light fixtures to couches, are standardized across the campus and are chosen by a few central administrators, and the students who live in the houses have little influence over the design process.

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<sup>35</sup> The architecture of Yazd has evolved to perform well, from a thermal perspective, in the desert climate. Buildings have high thermal mass to take advantage of diurnal temperature variations and advanced natural ventilation systems, including ventilation towers that catch the prevailing winds and keep interior spaces cool.

The generative design process at Williams often produces the type of space shown on the left, where the furnishings are well conformed to the size, character, and purpose of the room. Here, there are many *Levels of Scale* (e.g. rug patterns, curtain folds, book spines, window panes, couch cushions, lampshade, various couch sizes, etc.) and the room is filled with adaptable features (e.g. adjustable curtains, operable windows, a moveable lamp, dimmable lighting options, couch cushions, multiple types and scales of seating). The space appears comfortable and quite functional as an intimate social lounge or study library. Residential spaces at Amherst, on the other hand, often feel more sterile, institutional, and underutilized because of the top-down process by which they are designed and maintained. The room on the right feels colder, emptier, and less lived in than its equivalent space at Williams. Often, the people who use rooms like these firsthand are quite effective at creating spatial arrangements that fit their behavioral and psychological needs.

A fundamental indicator of artificial structure is the standardization of form at many scales. This results from the use of identical modular parts in construction. Building components are usually fabricated off-site and out of context based on a few generic shapes and patterns. Like the overall blueprint, these modular parts cannot easily conform to the highly specific functional requirements of the unique environmental systems into which they are being introduced (Alexander, 2004).

Contemporary architecture has generally subscribed to the belief that generic, mass-produced components are the most efficient materials to use in building construction. Alexander suggests that this industrial-age faith in modularity as a pre-requisite for functionality arises from a prevalent 19<sup>th</sup> and 20<sup>th</sup> century intellectual belief that the fundamental building blocks of the universe itself are identical, standardized components (Alexander, 2004). More recently, however, atomic photographs have shown that every atom is geometrically unique. Leading theoretical physicists like David Bohm have suggested that the universe cannot be composed of identical components at any scale (Alexander, 2004; Bohm, 2002). Every part of the natural world develops its own form in order to function as efficiently as possible within its specific context, and no two contexts are alike (Alexander, 2004). In order to feel comfortable and function effectively, humans need architectural spaces as unique and contextualized as the universe itself.



**Figure 4.17: (Left) Complex organization of many unique parts (Venice neighborhood). (Right) Simplistic repetition of a few standardized parts (New York housing project).**

### **Complex order and degrees of life**

Generated natural structure, Alexander proposes, is inherently more efficient and functional than fabricated artificial structure. Natural structure tends to be present in complex adaptive systems, including highly functional buildings, whose parts continuously interact, adapt, and self-organize to generate a higher degree of systematic order. Natural structure therefore reflects efficient and resilient systems exhibiting a low degree of entropy and a high degree of ordered complexity (Salingaros, 2007).

Alexander proposes that the emergence of this ordered complexity in a system can be thought of as the phenomenon of “life” itself. Consistent with ecologists and other scientists, his definition of life extends beyond single biological organisms and also includes ecosystems, inorganic natural structures, and even some man-made infrastructure. “What we call ‘life,’” he writes, “is a general condition which exists, to some degree or other, in every part of space: brick, stone, grass, river, painting, building, daffodil, human being, forest, city. And further: the key to this idea is that every part of space – every connected region of space, small or large – has some degree of life, and that this degree of life is well defined, objectively existing, and measurable” (Alexander, 2002, p. 77).

This theory suggests that all man-made buildings and places can be described along a continuous spectrum according to the absolute degree of life, or ordered complexity, embodied in their physical structure (Figure 4.18). Alexander also argues that humans are instinctively capable of perceiving this complex order, or “life,” in any system, and that people

across cultures and demographics demonstrate consistent agreement when they compare the degrees of life of different places. Perceived life, he argues, is a fundamental and reliable quality by which all environments can be measured.

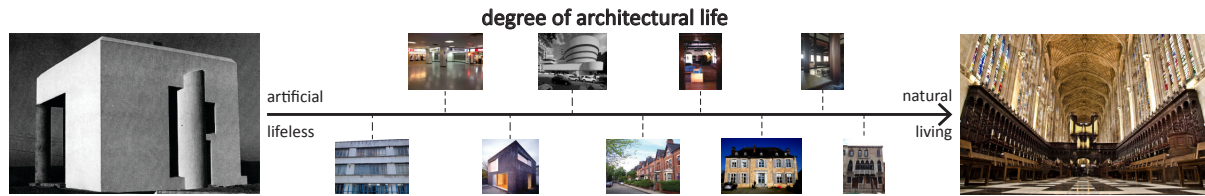


Figure 4.18: The "degree of life" spectrum

### Relationship to previous theories

Alexander's hypothesis is consistent with the theories presented by several scholars including E.O. Wilson, who argues that people are innately bonded to a "life-like" quality present not only in biological organisms but also in inorganic aspects of nature like mountains and sunlight (E. O. Wilson, 1984; E. O. Wilson & Kellert, 1995). In fact, the theory of natural structure complements the biophilia hypothesis by clarifying some of its underlying definitions and ambiguities, including the difficult man-made vs. natural conundrum. Broadening Wilson's main argument, Alexander proposes that humans are inherently drawn to all that is alive and vital in both the natural and built environments, and that the presence of complex order or "life" in an environment helps support cognitions and behaviors essential to human health (Alexander, 2002).

This theory also echoes language that many urban theorists since Jane Jacobs have used to describe great cities. In *The Death and Life of Great American Cities*, Jacobs uses terms such as "ecosystems" and "organisms" to describe cities embodying a high degree of ordered complexity, functionality, and "life" (Jacobs, 1992). The publication of Alexander's *Nature of Order* series has also coincided with the rise of the biophilic, biomorphic, and biomimetic architectural movements, three philosophies that recognize the importance of integrating natural structure into architectural design.<sup>36</sup>

<sup>36</sup> Biophilic design emphasizes the need to introduce natural elements (like trees, grass, water, etc.) into the built environment but does not necessarily address the quality of the architecture itself. Biomorphic design tends to model architectural form after specific shapes found in nature, often in a literal sense. Biomimetic architecture addresses specific functional challenges in the built environment (e.g. natural ventilation strategies) by drawing inspiration from analogous processes in specific organisms or ecosystems (e.g. self-cooling termite mounds).

While these three “bio-architecture” movements have arisen from a similar appreciation of the functional and experiential benefits of natural systems, they fall short of the integrated approach Alexander has proposed. Like most contemporary architecture they often promote rigid pre-fabricated designs rather than adaptive generative processes. Furthermore, buildings do not need to imitate other biological forms – particularly forms that have evolved for functional purposes irrelevant to human beings – in order to embody natural structure. According to Alexander, people are capable of building infinite varieties of their own “natural” infrastructure that is highly adapted to fundamental human needs if they are granted the freedom to undertake the appropriate building processes (Alexander, 2004).

### **Past research linking natural structure and wellbeing**

To the author’s knowledge, no previous research has deliberately tested the relationship between natural structure and wellbeing, but a number of studies suggest that this is a topic worthy of further investigation (see literature cited below). The research cited above demonstrating the health benefits of natural and adaptable environments provides the most compelling evidence. Other architectural research also points to potential correlations linking the geometric patterns Alexander has identified with healthy behaviors and psychological experiences. A few examples are summarized below.

*Boundaries:* A number of studies have investigated how the relative presence of semiprivate space surrounding residential houses affects social relationships (S. C. Brown et al., 2009; Cattell, Dines, Gesler, & Curtis, 2008; Skjaeveland & Garling, 1997; Williams, 2005; Yancey, 1971). In general, this research has indicated that environmental features like front porches, front gardens, and front stoops serve as semiprivate buffer zones that provide a more natural transition between private and public space and promote more consistent social interaction between neighbors. These boundaries, in fact, tend to serve as the fundamental places where spontaneous neighborly interaction occurs. Neighborhoods featuring substantial, semipermeable boundaries around individual houses often exhibit more reported friendships and greater social cohesion than those with abrupt transitions between private and public space. Boundary-related features of residential neighborhoods, such as sidewalks and front porches, were found to correlate positively with self-reported neighborliness in a study of 10 neighborhoods in Portland, Oregon (Wilkerson et al., 2011). Another study of 434 Chicago



residents identified a significant correlation between boundary-related home features, such as nearby open lawns with trees, and self-reported well-being (Hadavi, 2017).



**Figure 4.19: (Left) No boundary, abrupt transition between building and street (Photo Everywhere, 2015). (Right) Stronger boundary, more gradual private-to-public transition (Baguette, 2006).**

*Alternating repetition:* Many researchers have compared the effects of mixed-use development and single-use development on social patterns and aspects of wellbeing (Evans, 2014; Jacobs, 1992; Kyttä & Broberg, 2014). In general, evidence indicates that mixed-use neighborhoods tend to generate more exercise and outdoor social activity by creating a variety of attractions and destinations within walking distance of peoples' houses (Townshend, 2014). The pattern of mixed-use development is associated with Alexander's geometric property of *alternating repetition*.

*Local symmetries:* Alexander and Carey (1968) conducted an experiment measuring cognitive responses to 35 patterns of black and white squares arranged in different linear sequences. The experiment was intended to evaluate and rank order the relative perceived simplicity of the patterns as determined by five measures of simplicity: which could be found most quickly from a collection of patterns, which seemed simplest in the subjective opinion of the subject, which was easiest to remember, which was easiest to confuse with others, and which was easiest to describe in words. For each measure, the cognitive simplicity of the 35 patterns was almost perfectly accounted for by the relative numbers of local symmetries in the patterns (Alexander & Carey, 1968). This experiment supports the hypothesis that local symmetry is associated with a high degree of cognitively perceived order (Alexander & Carey, 1968; Salingaros, 2007).



**Figure 4.20: (Left) Single-use development accessible by car only (Quednau, 2016). (Right) Multi-use development encourages walking and public interaction (Gomes, 2014).**

These studies suggest that some of the fifteen properties, when considered individually, may support positive aspects of cognition and behavior. It is misleading, however, to consider the properties in isolation, because wherever they do occur, they tend to emerge together as a result of one integrated generative process. To the author’s knowledge, no previous research has directly measured the potential health benefits of the degree of ordered complexity, or “life,” that can emerge from this type of process.

## Conclusion

Environmental health researchers have long sought to find consistent relationships between architectural design features and wellbeing. A few well-established factors like air quality, natural lighting, privacy, occupant control, and greenery have consistently been found to improve occupant health. Still, leaders of the field have pointed out the limitations of measuring isolated environmental variables and have urged future researchers to seek more holistic measures of environmental qualities, including aesthetic qualities, that are relevant to human flourishing (Burton, 2014; Kyttä et al., 2011).

Christopher Alexander’s proposal that every place has a measurable degree of organized complexity, or “life,” based on its objective geometric order, presents an intriguing new definition of environmental quality that may be relevant to occupant well-being. Alexander has also developed a system for constructing buildings and urban neighborhoods with a high degree of life (Alexander, 2004), meaning that his theory, if supported, could be applied in a practical way to help architects and urban planners build healthier buildings. Can this quality



of *natural structure*, or “life,” be objectively measured in the built environment? Does this quality offer measurable value to human health? If so, could an increase in the natural structure of the environments we inhabit lead to a positive shift in the wellbeing of the general population? These urgent questions have motivated the experiments presented in the following chapter.

# **Chapter 5:**

## **Psychological responses to natural patterns in architecture**

### **Introduction**

The psychological benefits of *naturalness* have been widely documented in the environmental psychology literature (for a review, see Bowler, Buyung-Ali, Knight, & Pullin, 2010). The sensory qualities of natural environments have been found to improve mood, attention, and cognitive functioning (Berman et al., 2012, 2008; Berto, 2005; Bratman, Daily, et al., 2015; Bratman, Hamilton, & Daily, 2012; Bratman, Hamilton, Hahn, Daily, & Gross, 2015; S. Kaplan, 1995), among other salubrious effects. Nature-like design features can also be found in certain built environments that exhibit visual patterns inspired by biological systems (Alexander, 2002; Goldberger, 1996; Joye, 2007b; Salingaros, 2003; N. B. Solomon, 2002). Researchers have proposed that organic patterns in architecture may be innately preferred over synthetic forms, and that exposure to naturalistic architectural spaces may confer similar psychological benefits as interacting with nature itself (Alexander, 2002; Joye, 2007b; Kellert, 2005; Salingaros, 2007). However, these ideas have received little experimental scrutiny to date (Joye, 2007b). This final chapter examines whether subjective perceptions of naturalness in architectural scenes are driven by objective visual patterns and investigates whether these nature-like patterns are robust predictors of similarity evaluations and preference ratings of architectural scenes. This work paves the way for future researchers to explore how naturalistic patterns in the built environment influence restoration and wellbeing.

### **Psychological benefits of naturalness**

Previous research has shown that interacting with natural environments, compared to urban or built spaces, can confer important benefits for mental health. The salubrious effects of exposure to nature include improved mood (Barton & Pretty, 2010; Bowler et al., 2010; Valtchanov, Barton, & Ellard, 2010), reduced stress (Valtchanov et al., 2010; Villani & Riva, 2011), improved concentration and working memory performance (Berman et al., 2012, 2008; Berto, 2005; Bratman, Daily, et al., 2015; S. Kaplan, 1995), higher self-esteem (Barton & Pretty, 2010; Pretty et al., 2005), increased feelings of energy and vitality (Ryan et al., 2010),

and overall self-perceived health (Kardan, Gozdyra, et al., 2015). Views of nature have also been shown to reduce criminal behavior (Kuo & Sullivan, 2001) and improve recovery from surgery (Ulrich, 1984). In fact, merely looking at images and virtual representations of natural landscapes can induce many of these benefits (Berman et al., 2008; Berto, 2005; Valtchanov et al., 2010; Valtchanov & Ellard, 2015).

Two complementary theories, the *Biophilia Hypothesis (BH)* and *Attention Restoration Theory (ART)*, help frame these empirical findings. The BH states that humans are innately drawn to the living and life-like forms often encountered in natural environments (E. O. Wilson, 1984; E. O. Wilson & Kellert, 1995). Proponents of BH argue that people have a genetically-rooted need to seek contact with plants, animals, and natural places, which stems from our species' evolution in "biological – not artificial or manufactured – environment[s]" (Kellert, 2005, p. 123). The word *biophilia*, which means "love of life," emphasizes the emotional dimension of the human-nature connection. ART, on the other hand, focuses on the cognitive benefits people derive from interacting with nature. According to ART, softly fascinating sensory stimuli in nature engage our attention in an automatic, bottom-up manner, thereby replenishing the limited cognitive resources that govern top-down executive functions, such as concentrating on difficult tasks. Nature thereby "restores" attentional resources and facilitates better performance on demanding cognitive tasks (S. Kaplan, 1995; S. Kaplan & Berman, 2010). Together, BH and ART offer complementary perspectives to explain why contact with nature might generate pleasurable and restorative psychological experiences.

Although BH and ART are more relevant to this chapter, several other theories have also been proposed outlining potential mechanisms underlying the predicted psychological benefits of exposure to nature, including Ulrich's stress reduction theory (Ulrich et al., 1991) and Joye's theory of processing fluency (Joye, Steg, Ünal, & Pals, 2016). Ulrich's stress reduction theory focuses on the ways in which different environments can foster an individual's ability to recover from stress or, conversely, inhibit stress recovery. Ulrich et al. define *stress* as "the process by which an individual responds psychologically, physiologically, and often with behaviors, to a situation that challenges or threatens well-being" (Ulrich et al., 1991). Psychological components of the stress response include cognitive appraisal of the stress-inducing situation and negative emotional responses like fear, anger, and sadness. Physiological components of the stress response include activation of cardiovascular,

neuroendocrine, and musculoskeletal systems in response to the stressor. Behavioral responses to stressors can have diverse (and predominantly negative) manifestations including avoidance, substance use, and temporary declines in cognitive performance.

Importantly, Ulrich et al. emphasize the concept of *restoration*, which describes the process by which an individual recovers from a stressful experience. Unlike stress responses, the process of restoration involves positive changes in psychological states, attenuation of stress-related physiological processes, and desirable improvements in cognition and behavioral patterns. In other words, restoration can be thought of as the reversal of the initial stress response. The key concept of Ulrich's stress reduction theory is that natural environments facilitate *restoration* from stressful experiences more readily than urban or built spaces.

Like stress reduction theory, ART also emphasizes the idea that nature is restorative. However, while ART focuses specifically on the cognitive aspects of restoration (i.e., restoration of attention), stress reduction theory takes a broader view by also highlighting the psychological (e.g. mood) and physiological (e.g. neuroendocrine) aspects of the restoration process. Finally, Joye et al. (2016) theorize that the restorative effects of nature (Kaplan & Berman, 2010) may be mediated by the fact that natural scenes often contain internally repeated self-similar patterns (e.g. fractal shapes) that can be processed more *fluently* than the non-self-similar visual characteristics of many urban scenes. According to this view, the higher processing fluency of natural scenes results in a lower cognitive load and thereby fosters replenishment of cognitive resources and restoration of mood and attention (Joye et al., 2016).

In an effort to investigate these mechanisms more closely, (Berman et al., 2014) identified specific visual patterns that may contribute to the cognitive and affective benefits of natural environments. Using image statistics, they quantified several low-level spatial and color patterns that reliably predicted whether outdoor environments were perceived as natural or man-made. Common characteristics of natural environments included high density of curved edges and high frequency of contrast changes distributed throughout the scene. In a follow-up study, (Kardan, Demiralp, et al., 2015) demonstrated that these naturalistic visual features were highly predictive of aesthetic preference ratings, suggesting that low-level patterns of nature may play an important role in generating aesthetic pleasure.

These findings have intriguing implications for architectural design and urban planning. Despite the salutary effects of nature, most people today spend upwards of 90% of their lives inside buildings (Evans & McCoy, 1998). If the psychological benefits of natural environments are driven by measurable visual patterns, then could the visual properties of the built environment be manipulated to create more pleasurable and restorative spaces for human inhabitation? Could the implementation of naturalistic patterns in architecture improve occupants' mood and cognitive functioning (Joye, 2007b; Kellert, 2005)? If so, then understanding how to integrate the sensory characteristics of nature into the built environment could prove a powerful tool for enhancing mental health on a large scale (Ibarra et al., 2017).

### Nature-like patterns in architecture



**Figure 5.1: The Corinthian column's biologically-inspired design is evident in its tree-like structure and floral ornamentation (Tokkoro, 2018; Warder, 2008).**

Although natural and manmade environments are often classified as categorically distinct types of space (Karmanov & Hamel, 2008), many buildings across the globe exhibit nature-like characteristics. Naturalistic forms and patterns have long served as a fruitful source of inspiration for architects and builders around the world (Alexander, 2002; Joye, 2007b; Kellert, 2005; Ostwald, 2001; Salingaros, 2007). Kellert defines *organic design* as “building shapes and forms that directly, indirectly, and symbolically elicit a human affinity for natural features and processes” (Kellert, 2005, p. 128). Examples include literal imitations of animal and plant shapes in architectural ornamentation (Figure 5.1), engineering strategies that mimic the structural support mechanisms of biological organisms (Figure 5.2, Left), and nature-like patterns of scaling and proportionality abstracted from natural systems (Figure

5.2, Right). “These architectural elements,” writes Kellert, “evoke sentiments that tap into our inherent responses to the patterns, movement, light, shape, and space encountered in nature” (Kellert, 2005, p. 159).



**Figure 5.2: (Left) Sagrada Família’s structure is modeled after the branching canopies of trees (Joye, 2007b). (Right) Taj Mahal (Forget, 2009) exhibits geometric patterns characteristic of biological systems, including local symmetries and self-similar shapes that repeat at several scales.**

Not all human construction, however, has arisen from the design model of nature (Kellert, 2003). Architectural design often exhibits a different type of structural organization that is not rooted in nature’s blueprints, but that is instead derived from intellectually-generated concepts like Euclidean geometry and the Cartesian coordinate system. A number of scholars argue that idealized shapes like rectangles, spheres, flat surfaces, and straight lines (Figure 5.3) have become increasingly prevalent in Western architecture since the Second World War, while pointing out that these inorganic forms are quite alien to the complex visual structures of living, biological systems (Aldersey-Williams, 2004; Alexander, 2002; Joye, 2007; Kellert, 2005; Salingaros, 2007).<sup>37</sup> Some theorists make the case that the rise of Euclidean architecture in the 20<sup>th</sup> century was driven by conscious efforts to create shocking new structures that stood out in stark contrast from nature (Alexander, 2002; Salingaros, 1998, 2007). Others contend that an increased emphasis on utilitarianism in building construction has pushed architects away from using nature-based design models, which are often perceived as incompatible with the economic incentives and production systems that drive

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<sup>37</sup> Kellert characterizes *inorganic design* as architecture that “reflects an excessive reliance on fabricated materials, artificial lighting, controlled climatic conditions, straight-line geometries, homogeneity of design, scales rarely if ever encountered in nature, [and] substitution of the synthetic for the natural” (Kellert, 2005, p. 133).

contemporary development (Alexander, 2002; Joye, 2007b). Joye, for instance, writes that “modern building is often dictated by efficiency and economic motives, barely leaving room for symbolic and stylistic references to natural contents” (Joye, 2007b, p. 311). However, the notion that architectural design has trended towards more artificial-looking forms over the past century remains controversial, as many examples of nature-inspired architecture have emerged in contemporary design and construction. Examples of naturalistic forms in contemporary architecture include recent work by Light Earth Designs and the Center for Environmental Structure (Figure 5.4).



**Figure 5.3: (Left) Buildings in Brasilia, a city largely inspired by artificial geometric forms. (Right) The design of a university dormitory in Cambridge, England is characterized by synthetic shapes.**

How do natural vs. synthetic architectural forms impact human experience? Some scholars have asserted that humans are innately drawn to architectural forms that echo the organic qualities of nature (Alexander, 2002; Joye, 2006; Kellert, 2005; Ruskin, 1849; Salingaros, 2007). This idea bears a striking similarity to the aesthetic notions of philosopher Immanuel Kant,<sup>38</sup> who proposed that all truly beautiful man-made objects (including buildings) look as if they were created by nature.<sup>39</sup> Other researchers have argued that exposure to nature-like architectural patterns may induce similar psychological benefits as interacting with nature

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<sup>38</sup> Thanks to Gregor Hayn-Leichsenring, a collaborator at University of Pennsylvania, for drawing this theoretical parallel between biophilic design and Kant’s notions of aesthetics.

<sup>39</sup> Kant observed that natural as well as man-made objects can be beautiful. In his view, nature is beautiful if it looks man-made, and man-made objects are beautiful if they look natural (Kant, 2001). This vice versa ‘as if’ is the key to Kant’s concept of beauty. He proposed that the creation of beautiful objects requires inborn talent. During the act of creation, the so-called genius does not follow formalistic rules, but is instead guided by his or her natural intuition. Therefore, according to Kant, man-made beauty is closely associated with the quality of naturalness.



itself (Alexander, 2002; Joye, 2007b; Kellert, 2003; Salingaros, 2007). Kellert, for instance, writes that organic architecture “enrich[es] the human body, mind, and spirit by fostering positive experiences of nature in the built environment” (Kellert, 2005, p. 5). However, very little empirical work to date has tested theoretical claims that naturalistic architecture is either innately preferred or restorative (Joye, 2007b).



**Figure 5.4: Naturalistic forms in contemporary architecture. (Left) Cricket stadium in Rwanda by Light Earth Designs (Ramage, 2018). (Right) User-designed house in Berkeley, CA by Center for Environmental Structure (Alexander, 2018).**

A major challenge facing this line of research is the methodological difficulty of operationalizing *naturalness* in experiments. Reliable, objective measures of environmental naturalness are needed in order to investigate how this aesthetic quality influences psychological experiences. However, definitions of naturalness in the context of architecture are often ambiguous and inconsistent. For example, “natural architecture” can describe man-made structures that have nature-like characteristics, or it can refer to the presence of water, vegetation, and other natural features in and around buildings.<sup>40</sup> However, neither of these definitions fully captures the overall degree of naturalness of an architectural space, which often depends on complex interactions among a variety of natural and built elements (Alexander, 2002; Kellert, 2005).

Instead of evaluating specific natural and built elements independently, the approach taken here investigates how visual patterns distributed throughout entire architectural scenes influence the perception of naturalness. In other words, low-level sensory properties of whole

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<sup>40</sup> Biomorphic design, for instance, models architectural forms after biological structures, whereas biophilic design focuses on incorporating water, vegetation, and sunlight into the built environment.



scenes are measured rather than high-level semantic information derived from isolated objects within a scene (such as the amount of furniture in a room, or the number of trees surrounding a building). Low-level scene features are predicted to influence perceptions of naturalness independent of how much nature-related semantic content a scene contains. This prediction stems from previous evidence suggesting that semantic information can be carried by low-level scene features. For example, low-level edge and color patterns have previously been found to convey semantic information about order and naturalness (Kotabe et al., 2016a).<sup>41</sup>

Here, two complementary strategies are integrated, one empirically-motivated and the other theory-driven, for identifying natural features of architectural design. The first strategy uses image statistics to identify low-level spatial and color properties of architectural scenes that drive subjective naturalness ratings. This approach builds on previous experiments showing that low-level visual features strongly predict perceptions of naturalness in scenes of outdoor landscapes (Berman et al., 2014; Ibarra et al., 2017; Kardan, Demiralp, et al., 2015) and that naturalistic spatial and color features play a role in driving scene preference ratings (Kardan, Demiralp, et al., 2015). These low-level features, when integrated into architectural scenes, are predicted to evoke associations with the environmental quality of naturalness.

The second strategy is derived from the concept of *natural structure* (Alexander, 2002).<sup>42</sup> According to this theory, architecture exhibits naturalistic aesthetic qualities when the process by which it is constructed resembles the adaptive, structure-preserving processes of biological growth (Alexander, 2004).<sup>43</sup> When people build as nature does, Alexander argues, buildings develop nature-like geometric patterns in their structure, which are summarized as fifteen patterns of natural structure. Please see Chapter 4 (Figure 4.5) for a summary of these fifteen patterns. While some of these patterns are difficult to quantify, others lend themselves to empirical measurement. Intriguingly, two of the patterns – *Levels of Scale* and

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<sup>41</sup> This prediction is also motivated by the idea that representations of the natural world in architecture depend as much on intuitive recognition of visual patterns abstracted from natural systems as on explicit depictions of biological forms (Alexander, 2002; Joye, 2007b; Kellert, 2005; Salinas, 1998).

<sup>42</sup> This concept is often referred to as “living structure” in Alexander’s work (Alexander, 2002). However, the term “natural structure” is adopted here because it is more consistent with the language used in related research in environmental psychology and biophilic design.

<sup>43</sup> For detailed examples of adaptive construction processes, see Alexander (2004) *The process of creating life*.

*Contrast* – align closely with the low-level visual features that Berman et al. (2014) and Kardan et al. (2015) identified in their experimental work as predictable characteristics of natural environments. Consequently, these two patterns were chosen for investigation because 1) they are more readily quantifiable than many of the other patterns, and 2) proxies of these patterns have been found to correlate with naturalness in previous experiments involving non-architectural stimuli (Berman et al., 2014; Kardan et al., 2015). These two patterns (*Levels of Scale* and *Contrast*) are qualitatively described in Box 5.1. The subsequent experiments quantify them using image statistics and address the question of whether they predict subjective naturalness and preference ratings of architectural scenes.



FIGURE 5: (LEFT) A DOOR WITH MANY LEVELS OF SCALE. (RIGHT) A DOOR WITH FEW LEVELS OF SCALE.

Natural systems often exhibit many well-marked **LEVELS OF SCALE**, with small, incremental jumps between scales. The smallest structural components are connected to the largest components through a linked hierarchy of scales. Components often double or triple in size from one scale to the next, but any given component is rarely more than ten times larger than the component at the next-smallest scale. This pattern is visible in the incrementally-sized structural features of trees (trunk, limbs, branches, and twigs), cells (cell wall, organelles, nucleus, chromosomes), rivers (bends in the river, tributaries, eddies, edge pools), and many other systems (Alexander, 2002). In architecture, as in nature, levels of scale serve many functional purposes. Glazing bars can be used to subdivide large windows into smaller panes, creating variations in scale that help frame views to the outside while increasing the durability of the glass. In homes, variations in room size enable a variety of social functions to take place, from small alcoves that foster private contemplation to large rooms that host public gatherings (Alexander, 2002). Scaling variations in doors (Figure 5, Left) enhance the structural integrity of the frame and improve wayfinding by drawing visual attention to a key navigational threshold. The door on the right, by comparison, exhibits so little differentiation that it is nearly indistinguishable from the surrounding wall.

**CONTRAST** describes the presence of visibly-discernible opposites that are widely distributed throughout natural systems. The organization of these systems often depends on interactions among these opposites. Matter itself arises from interactions among opposite elementary particles, such as up vs. down quarks, particles vs. antiparticles, and positive vs. negative charges. On a larger scale, contrast is visible in the diurnal cycle of day and night, in the close interactions between static (solid) and mobile (liquid) phases in biochemical processes, and even in the juxtaposition of light and dark patterns on butterfly wings, which play an important role in mating behavior (Alexander, 2002). In architecture, contrast can take many forms. Black-white and dark-light contrasts are the most recognizable examples. Contrast also arises from juxtaposing complementary colors (e.g. red-green), contradictory textures (e.g. soft-hard), and opposite forms (e.g. solid-void) (Alexander, 2002). The house in Figure 6 (Left) exhibits several varieties of contrast: blue-orange contrast between the hues of shutters vs. masonry; rough-smooth contrast between the texture of masonry vs. glazing; small-large contrast in the size of stone embedded in the façade; and dynamic contrasts between straight lines and curves in the edges of windows, doorframe, and stonework. These counterbalanced features serve to differentiate and define structural elements of the house, while simultaneously uniting the individual components into a complex, organic whole. The school on the right, by comparison, contains fewer and weaker examples of contrast. Its façade exhibits far less differentiation in color, texture, brightness, and form, giving the building a more homogenous and artificial character.

FIGURE 6: (LEFT) INTENSE CONTRAST IN A FRENCH HOUSE (CARDESSE, FRANCE). (RIGHT) LESS INTENSE CONTRAST IN A SCHOOL FAÇADE (COVENTRY, ENGLAND).



**Box 5.1: Levels of Scale and Contrast, two proposed patterns of natural structure (Alexander, 2002).**

### Overview of experiments

The purpose of this research was to investigate whether subjective perceptions of naturalness are driven by objective spatial and color features of architectural scenes and to determine whether these naturalistic design features influence similarity ratings and aesthetic preferences of architectural scenes. These questions are addressed in four experiments. In Experiment 1, subjective naturalness ratings were collected of interior and exterior architectural images, and these ratings were regressed on eight low-level image features. It was predicted that low-level spatial and color patterns would explain a significant proportion of the variance in naturalness ratings, and that scenes exhibiting more *Levels of Scale* and greater visual *Contrast* (Alexander, 2002) would be perceived as more natural. In Experiment 2, participants were asked to evaluate the similarity of diverse architectural images using an image arrangement task. Multidimensional scaling analysis (MDS) was applied on these similarity data to identify the underlying aesthetic dimensions that drove participants' image arrangement decisions (Berman et al., 2014; Hout, Papesh, & Goldinger, 2013; Shepard, 1980), with the prediction that latent perceptions of naturalness would influence the way in which participants intuitively organized images. This prediction was tested by regressing dimension weights from the MDS analysis on subjective naturalness ratings collected in the first experiment. In Experiment 3, preference ratings for the architectural images were collected. This experiment tested the hypothesis that preferences would be strongly predicted by the naturalistic patterns quantified in Experiment 1. In the final experiment, correlations were examined between Modeled Naturalness and subjective perceptions of order, comfort, and excitement (proxies for the three psychological dimensions identified in Chapter 3) in order to understand the more nuanced aspects of psychological experience that are associated with viewing natural patterns in architectural scenes.

## **Experiment 1: Identifying nature-like patterns in architecture**

This experiment set out to determine whether subjective perceptions of naturalness are driven by objective low-level features of architectural scenes. It was predicted that low-level scene features would significantly predict naturalness ratings, and that architectural scenes exhibiting greater *Levels of Scale* and greater visual *Contrast* would be perceived as more natural.

### **Methods**

#### *Participants*

100 American adults (55 Women, 45 men) were recruited for this experiment from Amazon's Mechanical Turk (MTurk) to rate images of architectural spaces on their perceived level of naturalness. Sample size was determined by the goal of obtaining approximately 50 naturalness ratings per image (Kotabe et al., 2016b, 2017). Half of participants (Group 1) were assigned to rate images of interior spaces ( $n=50$ ), and the other half (Group 2) were assigned to rate images of exterior spaces ( $n=50$ ). Ages ranged from 21 to 65 years ( $M = 34.6$ ,  $SD = 9.6$ ). In terms of ethnicity, 75 participants identified as white, 11 as African American, 9 as Asian, 4 as Hispanic, and 1 as Multiple Ethnicities. Income ranged from under \$10,000 per year to over \$150,000 per year ( $M = 41,200$ ,  $SD = 29,890$ ). In terms of highest educational degree attained, 4 participants listed a postgraduate professional degree, 2 listed a Master's degree, 44 listed a Bachelor's degree, 10 listed an Associate's degree, 22 listed having some college education with no degree, 17 listed a high school degree, and 1 participant had some high school education with no degree. Data was excluded from 8 participants who gave the same naturalness rating for 10 or more consecutive stimuli at least once during their individual trial. This response pattern suggested that they were likely clicking through the images and not attending to the assigned task. All participants were compensated \$1.00 for their participation and the experiment took approximately 10 minutes to complete. Informed

consent was obtained through the Institutional Review Board (IRB) of the University of Chicago.<sup>44</sup>

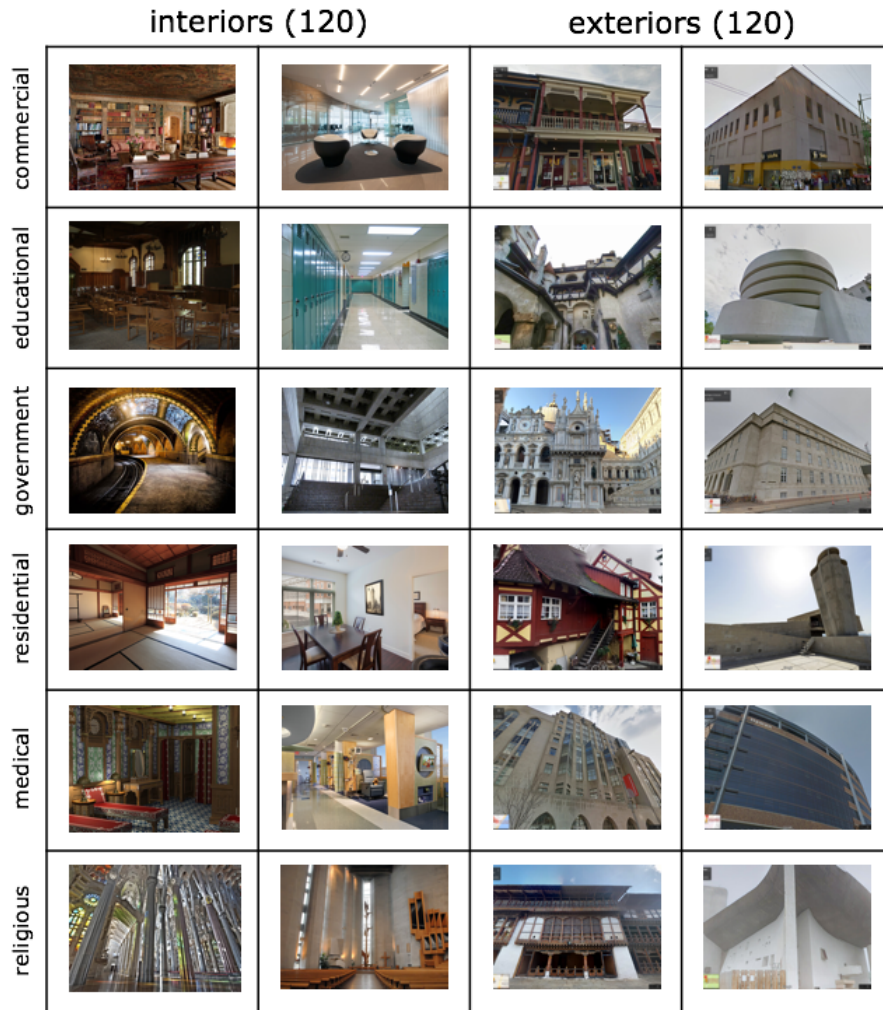
### *Materials*

Two sets of stimuli were used in all three experiments of this study: 120 images of architectural interiors and 120 images of architectural exteriors. Interior photographs were chosen from a variety of online public domain collections of architectural images. Exterior photographs were taken from the Street View interface of Google Earth and were restricted to head-on shots of buildings taken at a distance of 20-30 feet from the façade. Within each 120-image stimulus set, twenty diverse examples of architectural spaces were chosen for each of six building types (commercial, educational, government, residential, medical, and religious).<sup>45</sup> This selection process strengthened the external validity of the study by exposing participants to a variety of architectural spaces representative of diverse building types one would encounter in the real world. It also enabled us to control for the potentially confounding effect of building function on architectural evaluations and ensured that both stimulus sets contained the same distribution of images across all six functional categories, thus facilitating more reliable comparison between interior and exterior results. The amount of vegetation (i.e. plants and trees) depicted in the image sets was intentionally minimized in the selection process in order to reduce the confounding effects of non-architectural natural features on subjective naturalness ratings of buildings. Images were normalized to 4:3 width-to-height ratios with dimensions of 1175\*881 pixels for exteriors and 1000\*750 pixels for interiors to ensure dimensional consistency across each image set. The images can be downloaded here: <https://github.com/alexcoburn11/Natural-Buildings-Images>.

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<sup>44</sup> The experiments described in this chapter were funded by the Environmental Neuroscience Laboratory at the University of Chicago. Hiroki Kotabe, a collaborator in that lab, was responsible for collecting data for the MTurk experiments.

<sup>45</sup> Although this is not an exhaustive list of possible building functions, it fulfilled the purpose of diversifying scene stimuli and balancing both image sets across a range of functional categories.



### *Procedure*

Participants rated images using the online interface of Qualtrics survey software. Participants in Group 1 (n=50) were shown the 120-image set of interior architectural spaces in a randomized order and were asked to rate each image in response to the prompt, “How artificial or natural does this building interior look to you?” Answer choices were presented on a standard 7-point Likert scale, with 1 indicating “very artificial” and 7 indicating “very natural.” Participants were given unlimited time to rate each image. The same procedure was followed for participants in Group 2 (n=50), except that they were asked to rate the set of 120-image set of architectural exteriors rather than interior spaces.

### *Quantifying spatial and color properties of architecture*

Three spatial properties and six color properties of each scene were measured in order to estimate the degree to which naturalness ratings could be statistically explained by these objective visual features. There are many possible ways in which visual properties of images

can be analyzed. Here, a set of nine visual features were measured that had been assessed in two previous studies investigating the low-level visual correlates of naturalness in outdoor spaces (Berman et al., 2014; Kardan, Demiralp, et al., 2015). These particular measures were chosen for three reasons: 1) they have straightforward interpretations; 2) they can be easily manipulated in visual stimuli by researchers and in built environments by architectural designers; and 3) they are theoretically relevant the patterns of natural structure (Alexander, 2002) described in the introduction.<sup>46</sup>

### Spatial Properties

Three spatial features of the images were calculated in this study. 1) **Edge Density** is a measure of how many straight and curved edges are in an image. This statistic was calculated using methods described in (Berman et al., 2014; Kardan, Demiralp, et al., 2015). The term “edges” describes points of discontinuity in brightness in an image that represent object boundaries and small-scale details of texture. Edge maps were calculated for each scene using MATLAB’s built-in Canny edge detection algorithm. Edge density was calculated from these edge maps as the sum of total edge pixel values (0 for non-edge pixels, 0.5 for faint edges, 1 for strong edges) divided by the total number of pixels in the image.

2) **Fractal Dimension**, as measured in this study, captures the visual complexity and scaling differentiation of the edge maps of the architectural images. Unlike smooth Euclidean shapes, fractals are fractured shapes consisting of self-similar patterns that occur on many scales of magnification, “building scale-invariant shapes of immense complexity” (Taylor et al., 2005, p. 91). Whereas a smooth Euclidean curve has a fractal dimension close to 1, a densely convoluted line that approximates the appearance of a two-dimensional surface has a fractal dimension closer to 2. Fractal dimension was calculated here by creating edge maps of the architectural images using the built-in Canny edge detection function in MATLAB. The fractal dimension of each image’s edge map was then calculated using the “boxcount” algorithm in

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<sup>46</sup> All of these low-level visual features were calculated using MATLAB by Omid Kardan, a PhD student and collaborator in the Department of Psychology at the University of Chicago.

MATLAB (Moisy, 2008), which applies the box-counting technique documented in (Taylor et al., 2005).<sup>47</sup>

3) **Entropy** is a statistical measure of randomness in a scene that is calculated using the scene's intensity histogram. A histogram of a gray scale image shows the distribution of intensity values of all the pixels that comprise the image. For an 8-bit grayscale image, each pixel could have an intensity value of 0-255. If the histogram of such an image has 256 bins (i.e., one bin for each possible intensity value), then the probability value of the  $n$ th bin of the histogram ( $p_n$ ) is calculated as the number of pixels with an intensity value of  $n-1$  divided by the total number of pixels in the image. Entropy was calculated using the following equation:

$$Entropy = - \sum_{n=1}^{256} (p_n * \log_2 p_n)$$

This equation (Kardan, Demiralp, et al., 2015) gives an estimate of the average information content of an image. High entropy values indicate that all possible intensity values in an image occur with the same probability (i.e., the intensity histogram represents a uniform distribution), suggesting that there is a high degree of randomness in the distribution of intensity values. Conversely, low entropy values indicate that the distribution of intensity values throughout a scene are non-uniform (i.e., non-random), suggesting more redundancy in informational content of the image.

### Color Properties

Six color properties of the images were calculated based on the standard hue-saturation-value (HSV) model using the built-in functions of MATLAB image processing toolbox (MATLAB and Image Processing Toolbox Release 2016b, The MathWorks, Inc., Natick, MA, USA). **Hue** is a measure of the average color appearance of an image (i.e., the dominant color wavelength of the scene). **Saturation** describes the intensity or purity of colors in a scene (i.e., the ratio of the dominant wavelength to all other wavelengths in a color). **Brightness** captures the

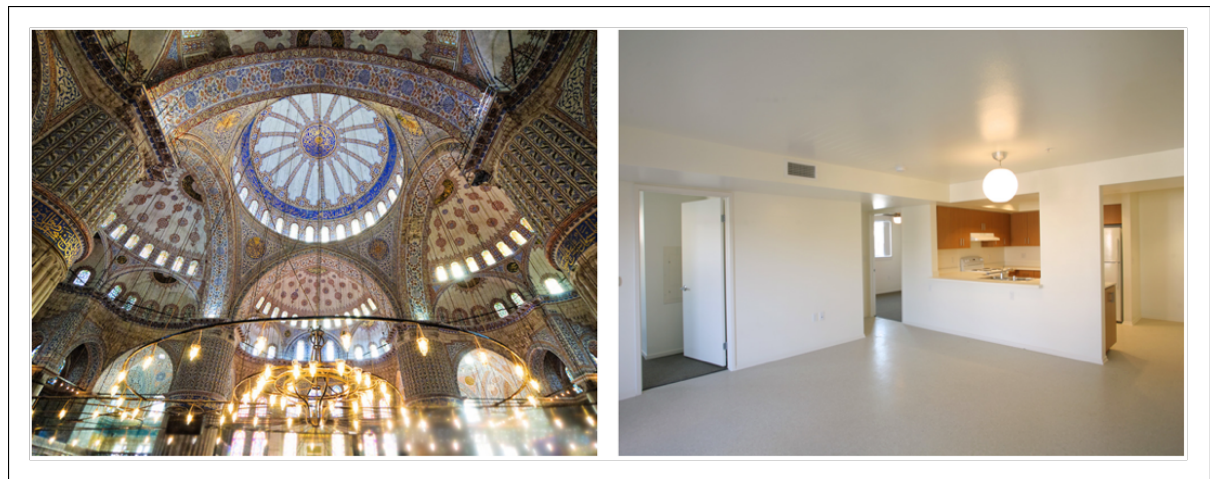
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<sup>47</sup> The box-counting method counts the number ( $N$ ) of identical 2-dimensional boxes of size ( $R$ ) needed to cover all edges (i.e., all nonzero pixels) in the image. This analysis is repeated for boxes with a range of square sizes. Each decrease in box size ( $R$ ) represents an increase in magnification. Box sizes vary by powers of two, i.e.,  $R = 1, 2, 4 \dots 2^P$  where  $P$  is the smallest integer such that  $2^P$  is smaller than the total image size. For fractal images,  $N$  scales according to the equation  $N = R^{-D}$ , where  $D$  is the fractal dimension of the image and  $1 < D < 2$ .



average luminance or value of an image. Standard deviations of these three color properties were also measured to quantify the diversity of hue (***sdHue***), the diversity of saturation (***sdSat***), and the diversity of brightness (***sdBright***) in each image. Calculations of all image statistics were normalized to the size of each image by dividing by the total number of pixels in the image. After all nine low-level visual features were calculated, values were standardized for each statistic by calculating Z-scores within each image set.

### *Quantifying Levels of Scale and Contrast*



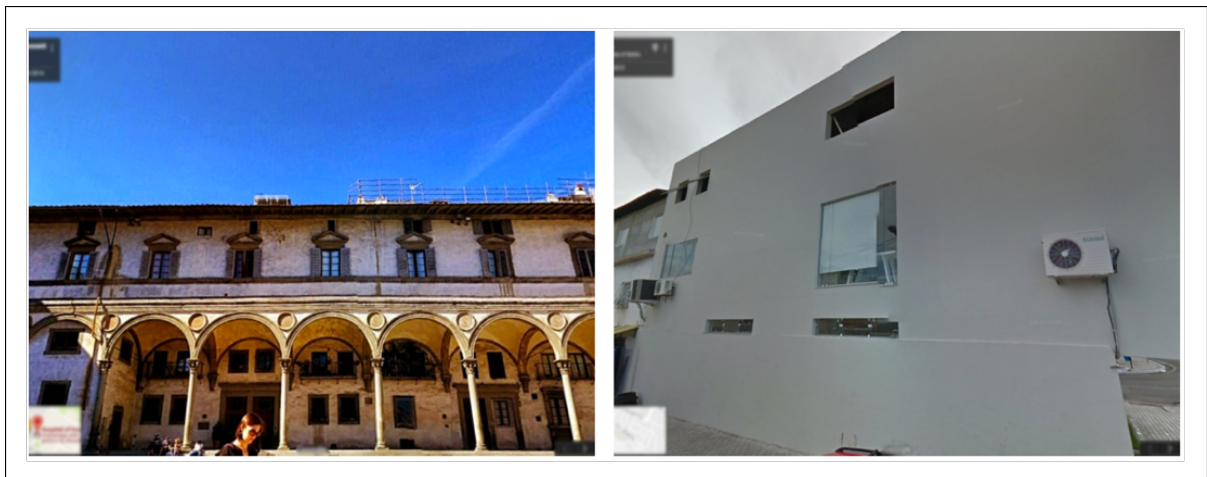
**Figure 5.5:** (Left) Interior scene with high values of edge density ( $Z = +2.56$ ) and fractal dimension ( $Z = +1.77$ ). (Right) Interior scene with low values of edge density ( $Z = -2.01$ ) and fractal dimension ( $Z = -2.73$ ).

Several of these image statistics were used to operationalize two of Alexander's proposed patterns of natural structure, *Levels of Scale* and *Contrast* (Alexander, 2002). When buildings exhibit many *Levels of Scale*, the smallest structural details are connected to the largest visible components through a linked hierarchy of scales. The Fractal Dimension measure is a close approximation of this pattern, since it measures the degree to which edge patterns in an image repeat at many scales of magnification. Architectural scenes with low Fractal Dimension values (approaching 1) are likely to depict smooth, sparse surfaces with little scaling differentiation and with large jumps between scales. Images with high Fractal Dimension values (approaching 2)<sup>48</sup> generally depict more intricate, detailed structures (Taylor et al., 2005), with more scales present and smaller jumps in between scales. A high degree of scaling differentiation is also generally associated with a greater density of small-

<sup>48</sup> This is because images are 2-Dimensional.

scale details, whereas less differentiated (i.e., minimalist) spaces typically contain less detail. Edge Density, which captures the amount of detailed edges in a scene, is therefore another close proxy for Alexander's *Levels of Scale* pattern.

The *Contrast* pattern was evaluated using three of the low-level color features described above, sdHue, sdSat, and sdBright. These three statistics represent the diversity of hue, saturation, and brightness distributed throughout an architectural scene. They provide estimates of two different types of visual contrast: color contrast (sdHue and sdSat) and brightness contrast (sdBright). These are by no means the only types of contrast that can exist in a building (see Box 5.1 for more examples of contrast). However, they are straightforward and easily quantifiable examples of color-related contrast features. It was predicted that all five of these statistical proxies of *Levels of Scale* and *Contrast* would correlate positively with naturalness ratings for both interior and exterior image sets.



**Figure 5.6:** (Left) Exterior scene with high values of sdHue ( $Z = +0.83$ ), sdSat ( $Z = +2.20$ ), and sdBright ( $Z = +2.02$ ). (Right) Exterior scene with low values of sdHue ( $Z = -0.79$ ), sdSat ( $Z = -1.67$ ), and sdBright ( $Z = -1.70$ ).

### Checking for redundant measures

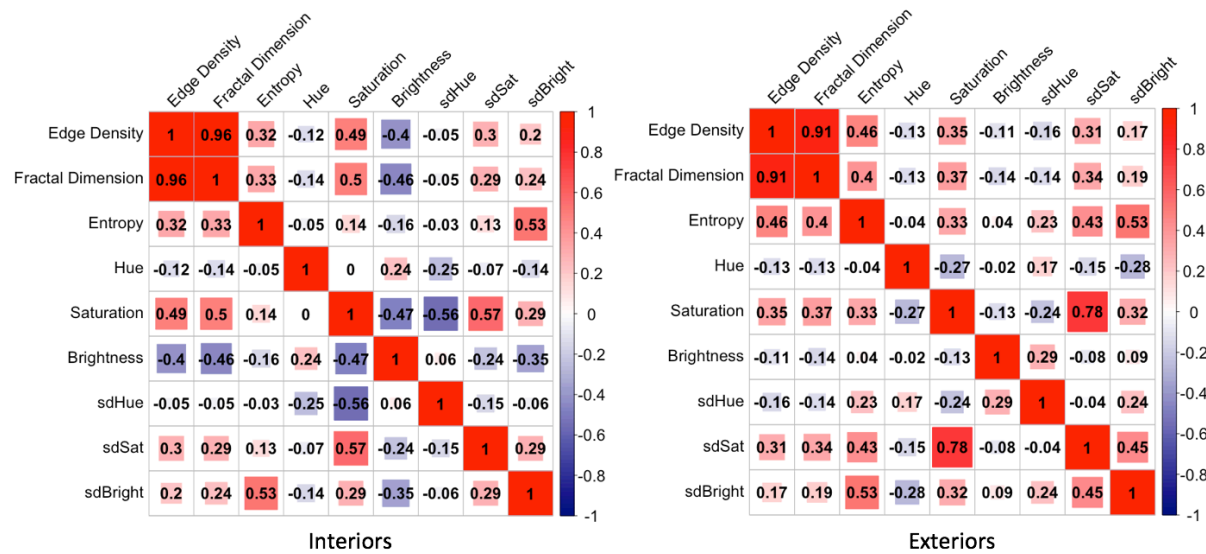


Figure 5.7: Correlation matrices of image statistics for Interiors (Left) and Exteriors (Right)

Next, correlation matrices were computed for interior and exterior image sets to check for multicollinearity in the low-level visual features (Figure 5.7). The threshold for multicollinearity was set at  $r = 0.8$ , which is the threshold that Field et al. (2014) recommend for eliminating redundant variables. Edge Density and Fractal Dimension were highly correlated in both interior ( $r = 0.96$ ) and exterior ( $r = 0.91$ ) images, indicating that these were essentially redundant measures. These variables were combined by calculating the average values of Edge Density and Fractal Dimension for each image. This new combined variable was labeled *Scaling*, since both of the measures that are theoretically linked to Alexander's *Levels of Scale* pattern.

### Quantifying Explicit Nature

In order to control for the natural vegetation content of the architectural scenes, the presence of explicit natural content in the stimuli was minimized during the image selection process. Additionally, the number of pixels in each scene depicting any remaining natural vegetation (e.g. grass, bushes, trees, flowerpots) was measured using the Quick Selection tool in Adobe Photoshop, and this value was then divided by the total pixel area of the scene. The resulting variable, which was labeled *Explicit Nature*, represented the proportion of image area occupied by vegetation in each architectural scene. This variable was added to regression models to control for the presence of vegetation in the architectural scenes.

*Statistical analysis*

Analyses were conducted at the image level by calculating average naturalness ratings for each image across all participants. Linear multiple regression models were constructed to examine the relationship between low-level visual features and mean naturalness ratings of interior and exterior image sets. In a second pair of analyses, naturalness ratings were regressed on Explicit Nature scores to determine the effect of high-level semantic content on subjective perceptions of naturalness.

**Results***Spatial and color features predict perceptions of naturalness*

A linear multiple regression model was constructed for the data from Group 1 participants (the group who was shown the images of interiors) by regressing mean naturalness ratings of the interior images on eight low-level spatial and color features. The Explicit Nature variable was added to the regression model to control for the amount of vegetation present in the scenes. The majority of the variance in mean naturalness ratings was collectively explained by these nine visual features [ $R^2_{\text{adj}} = 0.66$ ,  $F(9, 110) = 26.40$ ,  $P < .001$ ]. The eight low-level visual features independently explained over half (54%) of the variance in naturalness ratings when controlling for Explicit Nature.<sup>49</sup> The same analysis was performed on the data from Group 2 participants (the group who was shown the images of exteriors). The nine visual features of exterior images also significantly predicted their mean naturalness ratings [ $R^2_{\text{adj}} = 0.52$ ,  $F(9, 110) = 15.04$ ,  $P < .001$ ]. When controlling for Explicit Nature, the eight low-level visual features independently explained 42% of the variance in naturalness ratings for exterior scenes. The results of these two regressions build on previous work showing that low-level visual features significantly predict the perception of naturalness in outdoor environmental scenes (Berman et al., 2014; Kardan, Demiralp, et al., 2015), many of which contained little or no built structure. Here, these past findings are extended to images of the built environment.

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<sup>49</sup> The relatively low amount of variance explained by Explicit Nature was likely influenced by the fact that scenes with minimal plants and vegetation were intentionally chosen in the image selection process in order to minimize the confounding effects of non-architectural references to nature on perceptions of naturalness.

As shown in Table 5.1 and Table 5.2, as well as in Figure 5.8, higher values of Scaling, sdSat, and sdBright significantly predicted higher naturalness scores for both interior and exterior architectural spaces. Additionally, Brightness correlated negatively with naturalness for interior scenes, although this effect was barely significant ( $P = 0.045$ ). Since images with high Scaling values are indicative of greater scaling differentiation in architectural design, the strong positive correlation found for this measure supports the hypothesis that incremental scaling is associated with the perception of naturalness in architectural scenes, whereas images of buildings with more abrupt changes in scale are more likely to be perceived as artificial-looking. The Scaling measure independently explained 31.7% and 15.8% of variance in naturalness ratings for interior and exterior scenes, respectively.

**Table 5.1: Regression of naturalness ratings vs. image features (Interiors)**

Visual Feature	Estimate	SE	$\beta_{ST}$	t value	P value	$n_p^2$
Scaling***	0.452	0.063	0.507	7.149	< .001	0.317
Entropy	-0.102	0.059	-0.116	-1.723	0.088	0.026
Hue	-0.044	0.051	-0.050	-0.855	0.395	0.007
Saturation	0.118	0.089	0.134	1.327	0.187	0.016
Brightness*	-0.122	0.060	-0.139	-2.031	0.045	0.036
sdHue	-0.106	0.066	-0.120	-1.614	0.109	0.023
sdSat*	0.136	0.061	0.154	2.241	0.027	0.044
sdBright**	0.173	0.061	0.196	2.817	0.006	0.067
Explicit Nature**	7.174	2.517	0.157	2.851	0.005	0.069

$R^2_{adj} = 0.66$ ,  $F(9, 110) = 26.40$ ,  $P < .001$

**Table 5.2: Regression of naturalness ratings vs. image features (Exteriors)**

Visual Feature	Estimate	SE	$\beta_{ST}$	t value	P value	$n_p^2$
Scaling***	0.289	0.064	0.352	4.543	< .001	0.158
Entropy	-0.107	0.071	-0.133	-1.518	0.132	0.021
Hue	-0.016	0.058	-0.019	-0.268	0.789	0.001
Saturation	-0.106	0.090	-0.132	-1.176	0.242	0.012
Brightness	0.066	0.054	0.082	1.222	0.225	0.013
sdHue	0.027	0.061	0.033	0.437	0.663	0.002
sdSat***	0.362	0.090	0.451	4.029	< .001	0.129
sdBright**	0.227	0.071	0.282	3.191	0.002	0.085
Explicit Nature**	1.716	0.631	0.189	2.719	0.008	0.063

$R^2_{adj} = 0.52$ ,  $F(9, 110) = 15.04$ ,  $P < .001$

Furthermore, two of the three features of color contrast – sdSat and sdBright – correlated significantly with naturalness in both image sets, thus supporting the hypothesis that greater visual contrast is positively associated with the perception of naturalness in architectural scenes (see Box 5.1). This effect, however, was limited to saturation and brightness-related contrast patterns, as hue diversity (sdHue) was not a significant predictor of naturalness in

either image set. The contrast-related measures independently explained 13.4% and 21.6% of variance in naturalness ratings for interior and exterior scenes, respectively.

In summary, these results show consistent relationships between low-level visual features, especially Scaling and Contrast-related patterns, and subjective perceptions of naturalness for both interior and exterior architectural scenes. Since both regression models controlled for the effect of vegetation on naturalness ratings, the results imply that Scaling and Contrast-related patterns visible in the buildings themselves, rather than in the trees and plants surrounding them, were driving perceptions of naturalness for these two image sets. These findings are consistent with the hypothesis that two of Alexander's proposed patterns of natural structure – *Levels of Scale* and *Contrast* – are positively associated with perceptions of naturalness in architectural design.

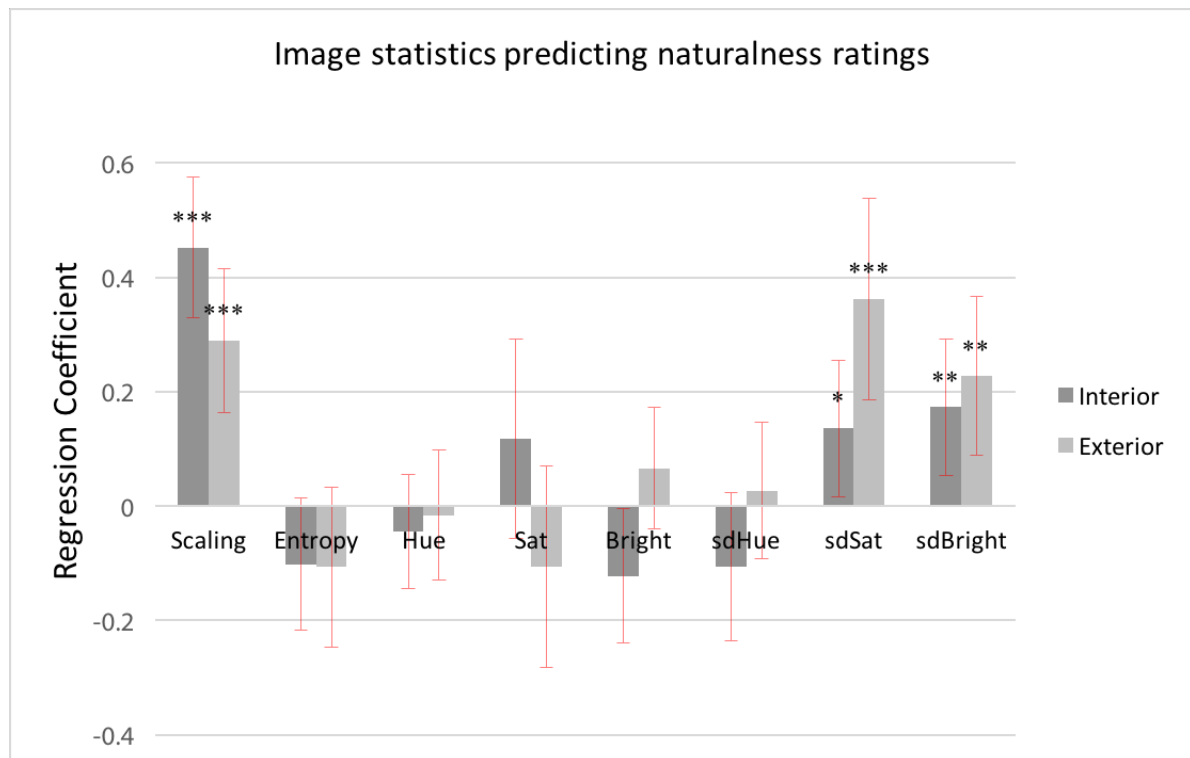


Figure 5.8: Coefficients of image statistics as predictors of naturalness for exterior and interior image sets, controlling for Explicit Nature. Error bars represent 95% confidence intervals of coefficient values.

## Experiment 2: Does naturalness of buildings influence similarity perceptions?

This experiment investigated whether latent perceptions of natural patterns in architectural scenes influence intuitive judgments of scene similarity. First, naïve participants assessed the

similarity of diverse architectural images in an image arrangement task referred to as the *spatial arrangement method (SpAM)* (Hout, Goldinger, & Ferguson, 2013). Multidimensional scaling analysis (MDS) was then applied on these similarity data to identify the underlying aesthetic dimensions that drove participants' grouping decisions (Berman et al., 2014; Hout et al., 2015; Hout, Papesh, et al., 2013; Shepard, 1980). It was predicted that latent perceptions of naturalness would strongly predict image grouping decisions. This prediction was tested by regressing dimension weights from the MDS analysis on subjective naturalness ratings collected in the first experiment, and by regressing dimension weights on naturalistic low-level visual features. These variables were chosen to include in the regression models in order to test whether people intuitively “see” nature-like patterns in architecture without needing any prompting to do so, as Alexander (2002) suggests. Many other architectural variables (including building age, enclosure, and ceiling height, to name just a few) could have been regressed against MDS dimension weights in a similar fashion. However, testing the effects of these other architectural features on similarity perceptions would have been peripheral to this central research question.

## Methods

### *Participants*

One hundred and sixty-seven participants, 81 from the University of Chicago, and 86 from New Mexico State University, took part in this study.<sup>50</sup> All participants provided written informed consent. University of Chicago participants were paid \$10 for participating in the study, and participants from New Mexico State University were compensated with partial course credit towards introductory psychology courses. Each participant completed the spatial arrangement task on one of four sets of stimuli (selection was counterbalanced across participants), which are referred to as Exteriors A (43 participants), Exteriors B (41 participants), Interiors A (41 participants), and Interiors B (42 participants).

### *Materials*

The stimuli used in this study were the same 240 images of interior (n=120) and exterior (n=120) architectural scenes used in Experiment 1. Here, however, each 120-image set was

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<sup>50</sup> Data for this experiment was collected by Omid Kardan and Arryn Robbins, collaborators at the University of Chicago, and by Arryn Robbins, a collaborator at New Mexico State University.

divided evenly into two sets of 66 interior scenes and two sets of 66 exterior scenes, with 12 images overlapping between the two sets for each scene type to check across sample stability of MDS dimensions. All photographs were JPG format, resized to 360x270 pixels so that multiple of them could be presented simultaneously (see procedure). Stimulus presentation was controlled by E-Prime vs 2.0 (Psychological Software Tools, 2012), presented on monitors that were 62.5 cm x 32.5 cm, at a resolution of 3840 x 2160.

### *Procedure*

On each trial, 20 different pictures were shown to the participant, randomly arranged in four rows of five items (evenly spaced along the x- and y-axes).<sup>51</sup> Participants were instructed to use the mouse to drag-and-drop the images in order to arrange them according to the participant's perceived similarity of each pair (with closer in space denoting proportionately greater similarity and vice versa; see Hout & Goldinger, 2016; Hout, Goldinger, et al., 2013). Participants were allowed as much time as they needed to arrange each set of pictures, and clicked on a small (100x100 pixels) image of a stop sign (placed in the bottom-most right corner of the display) to indicate that they were done arranging the stimuli. After clicking on the stop sign, they were provided with a prompt asking them if they were done arranging the stimuli, if they needed more time, or if they would like to start over. This prompt ensured that trials were not ended prematurely in the event that the stop sign was clicked by mistake. If the participant indicated that they would like to start over, all images were returned to their original starting configuration. When the participant indicated that they were done, the program recorded the x- and y-coordinates for each image, and the Euclidean distance between each pair (for 20 stimuli, there are 190 pairwise distances). This procedure was performed 18 times, with different sets of pictures on each trial, ensuring that each image was paired with every other image at least once. Therefore, each participant provided a complete similarity matrix for the set of 66 scenes (i.e., 2,145 pairwise distances).

The selection of images on each trial was controlled by employing a stimulus selection algorithm (MacDonald, Hout, & Schmidt, in preparation; algorithm code is available at

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<sup>51</sup> The interface for this experiment was designed in E-Prime by Michael Hout and Justin MacDonald, collaborators at New Mexico State University.



<http://justinmacdonald.net/publications>) that attempts to minimize the number of trials necessary to ensure that all possible pairings of pictures were included in at least one trial.<sup>52,53</sup> The algorithm chose 20-item subsets of the full set of 66 stimuli such that every pair of items was presented together on at least one trial, and the total number of trials was minimized. Because a list of subsets in which each pair of items is presented exactly once does not exist (for details, see (Horsley, 2017)), some items were paired with others on more than one trial. This leads to multiple observations per “cell,” so in such instances, the average of the multiple distances was used as the similarity rating for that pair. To balance out these redundancies, across participants, images were randomly assigned to numerical identifiers in the algorithmic set. This ensured that each participant saw each pair of pictures together at least once, but that different participants were presented with different redundant pairings.

### *Determining dimensionality of data*

Similarity data for each of the four sets of stimuli were subjected to multidimensional scaling via the PROXSCAL scaling algorithm (Busing, Commandeur, Heiser, Bandilla, & Faulbaum, 1997) implemented in SPSS software.<sup>54</sup> Metric MDS was performed, as Euclidean distances on the computer monitor are of ratio scale. To determine the appropriate dimensionality in which to scale the data, Scree plots were created, plotting the model’s stress against the number of dimensions used to locate the points in space. Stress functions measure the agreement between the modelled distances provided by the MDS output and the raw input proximities (i.e., the raw Euclidean distances between pairs). Lower stress values indicate better model fit. Scree plots are often used to determine dimensionality by having the analyst look for an “elbow” in the plot; that is, the point at which stress no longer decreases substantially with increased dimensionality. Pronounced elbows are not always present on Scree plots, however, and as you can see from the results, stress continued to decrease across

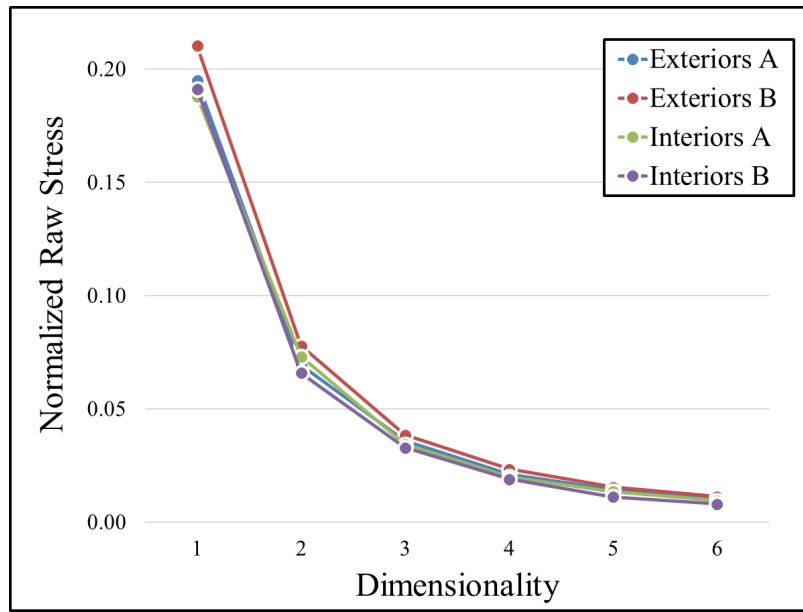
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<sup>52</sup> This stimulus selection algorithm was implemented by Justin MacDonald, a collaborator at New Mexico State University.

<sup>53</sup> This is a special case of the set cover problem in combinatorics (Vazirani, 2001): a block of  $k$  items is sampled repeatedly from a larger set of  $n$  items. How many blocks of items are necessary so that all possible  $t$ -sized subsets appear together within a block at least once ( $n > k > t$ )? In this experiment,  $n = 66$  items,  $k = 20$  items per trial, and  $t = 2$ , indicating that all 66-choose-2 item pairs were selected to appear in a 20-item trial at least once.

<sup>54</sup> The multidimensional scaling analysis described here was conducted by Michael Hout, a collaborator at New Mexico State University.

many dimensions, nearing zero at six dimensions for each of the four stimulus sets. It is also worth noting that the stress functions are remarkably similar for all four sets of images. When large sets of stimuli are employed in MDS, it is less deleterious to overestimate the dimensionality of the space than it is to underestimate dimensionality (Hout, Cunningham, Robbins, & MacDonald, 2018). As such, each of the stimulus sets was scaled in six dimensions.

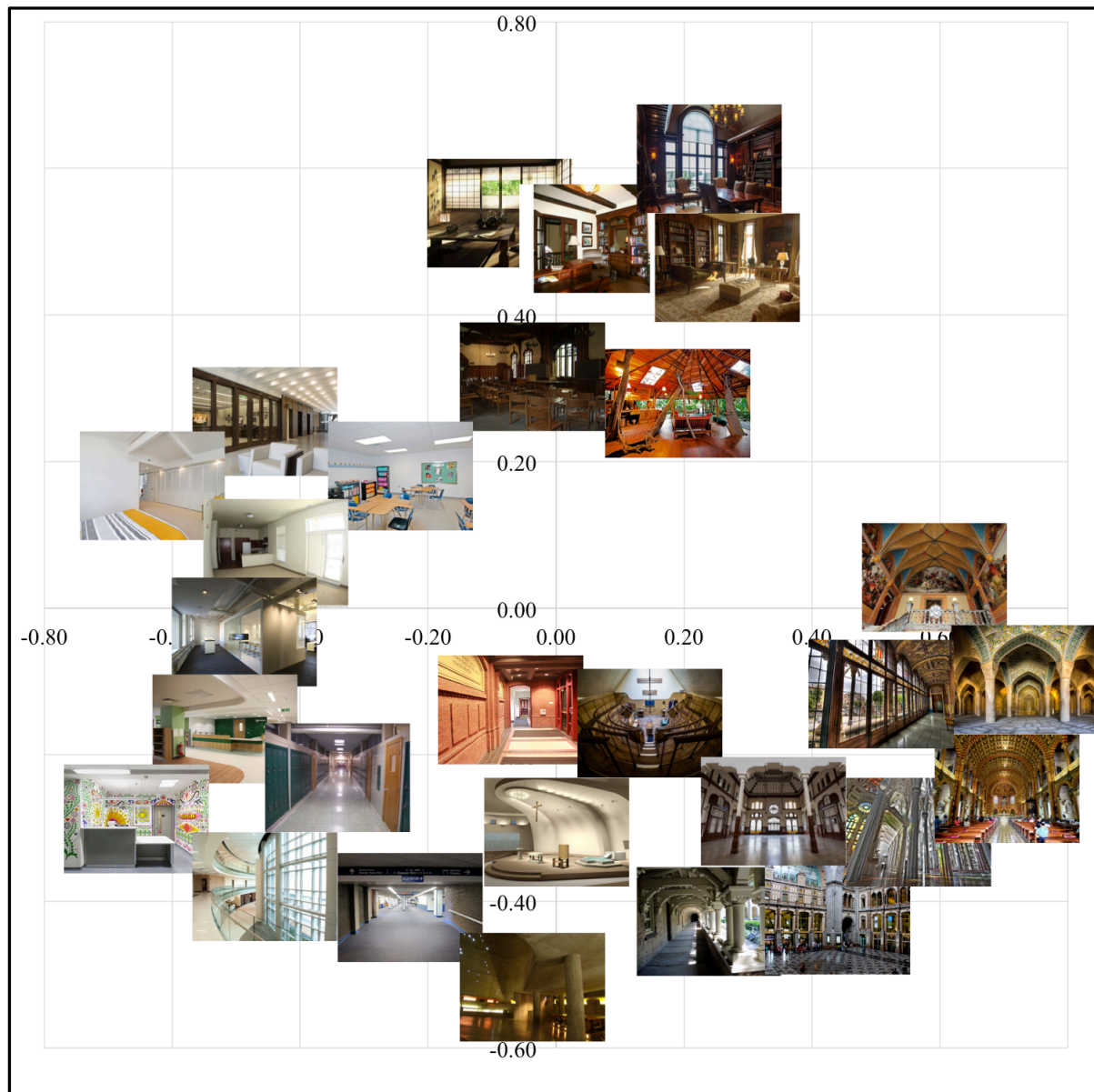


**Figure 5.9: Scree plots, showing normalized raw stress (for each of the four stimulus sets) plotted against the number of dimensions used in the MDS analysis.**

## Results

### *MDS analysis*

The results of the MDS analysis on the four sets of images are displayed in Figure 5.10, Figure 5.11, Figure 5.12, Figure 5.13, respectively. In those visualizations, the architectural images are superimposed on the MDS plot according to their weights on Dimension 1 (X-axis) and Dimension 2 (Y-axis). As mentioned, the data were scaled in six dimensions to yield the most appropriate overall spatial organization. However, the analysis here focused on the weights of the first two dimensions, as those dimensions explained the most variance in image similarity. At first glance, Dimension 1 appeared to code for the naturalness of the architectural scenes, with scenes depicting more naturalistic buildings having higher weights on Dimension 1, and with images depicting more artificial-looking buildings having lower weights on Dimension 1. Dimension 2 was more difficult to interpret. This pattern emerged across all four sets of images.



**Figure 5.10:** Plotted results of MDS dimension 1 (X-axis) and Dimension 2 (Y-axis) for the first image set (Interiors A). Pictures are superimposed based on their weights on Dimensions 1 and 2. A subset of the 66 images is plotted in order to make the graph more readable.



Figure 5.11: Plotted results of MDS dimension 1 (X-axis) and Dimension 2 (Y-axis) for the second image set (Interiors B). Pictures are superimposed based on their weights on Dimensions 1 and 2. A subset of the 66 images is plotted in order to make the graph more readable.



Figure 5.12: Plotted results of MDS dimension 1 (X-axis) and Dimension 2 (Y-axis) for the third image set (Exteriors A). Pictures are superimposed based on their weights on Dimensions 1 and 2. A subset of the 66 images is plotted in order to make the graph more readable.



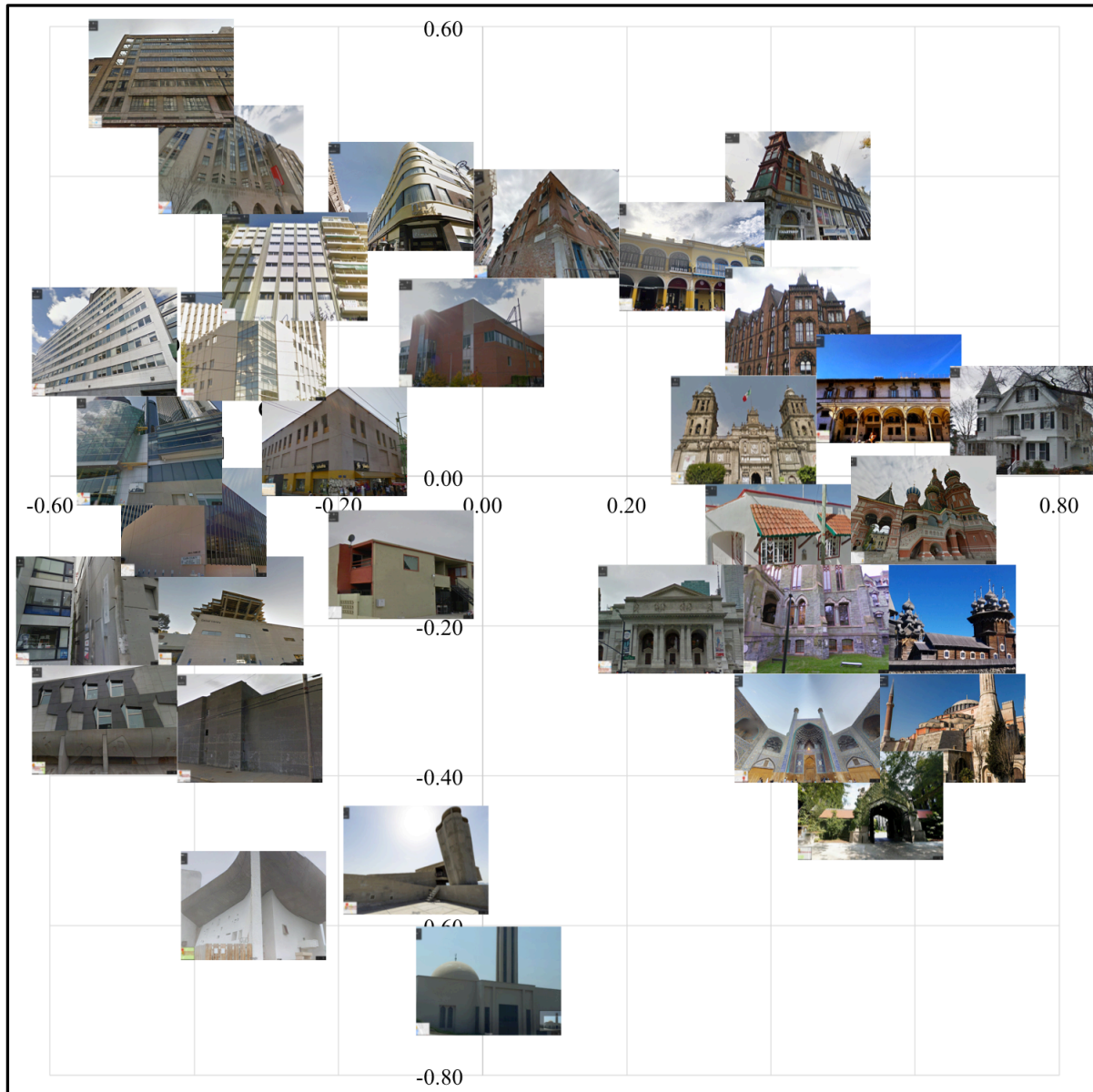
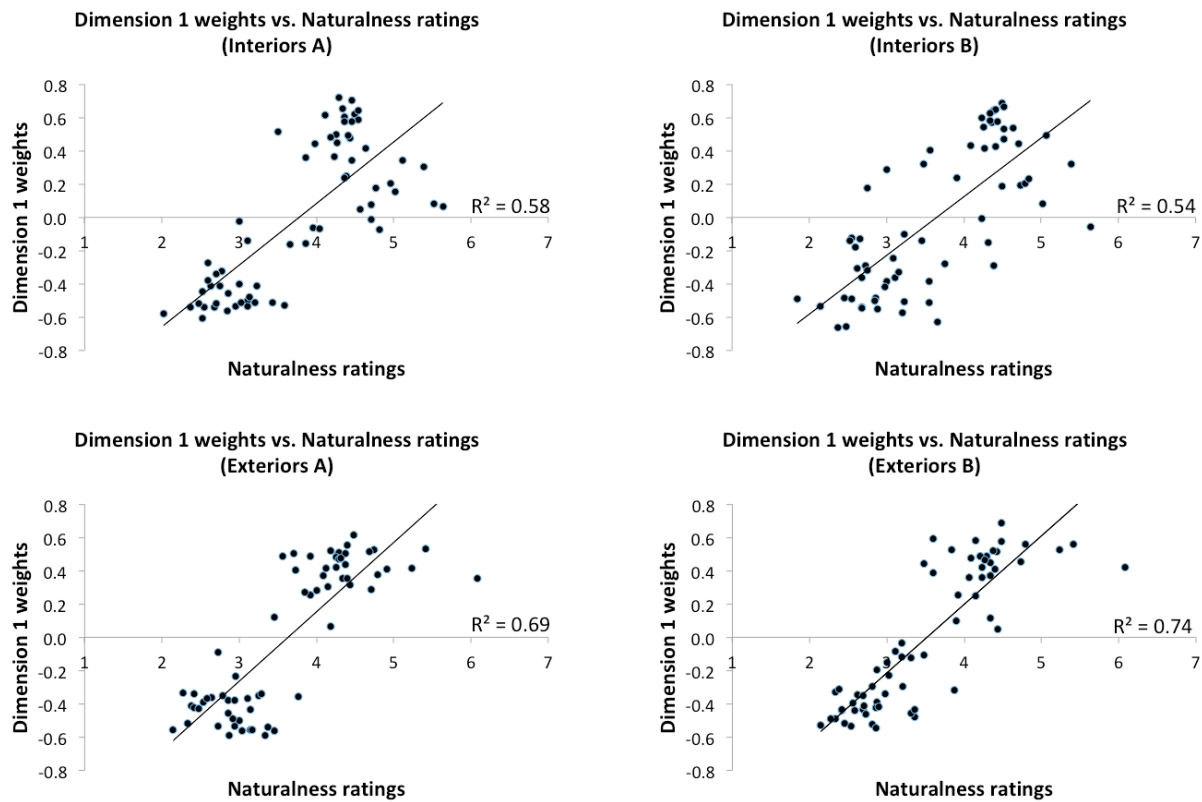


Figure 5.13: Plotted results of MDS dimension 1 (X-axis) and Dimension 2 (Y-axis) for the fourth image set (Exteriors B). Pictures are superimposed based on their weights on Dimensions 1 and 2. A subset of the 66 images is plotted in order to make the graph more readable.

### *Naturalness predicts similarity ratings*

To test whether Dimension 1 from the MDS analysis was coding for latent perceptions of naturalness, linear regression models were constructed of images' Dimension 1 weights as a function of their mean naturalness ratings (collected in Experiment 1). Subjective naturalness ratings significantly predicted Dimension 1 weights across all four sets of images. Naturalness ratings explained over half of the variance in Dimension 1 weights for Interiors A [ $R^2_{\text{adj}} = 0.57$ ,  $F(1, 64) = 88.02$ ,  $P < .001$ ] and Interiors B [ $R^2_{\text{adj}} = 0.53$ ,  $F(1, 64) = 73.87$ ,  $P < .001$ ] and over two-thirds of the variance in Dimension 1 weights for Exteriors A [ $R^2_{\text{adj}} = 0.68$ ,  $F(1, 64) = 141.1$ ,  $P <$

.001] and Exteriors B [ $R^2_{\text{adj}} = 0.73$ ,  $F(1, 64) = 179.6$ ,  $P < .001$ ]. Scatterplots showing correlations between naturalness ratings and Dimension 1 weights are shown in Figure 5.14.



**Figure 5.14: Correlations of Dimension 1 weights with Perceived Naturalness for the four sets of images.**

The significant correlations between subjective naturalness ratings and Dimension 1 weights across all four sets of images suggest that MDS Dimension 1 is likely coding for the perceived naturalness of architectural scenes. In other words, Dimension 1 can be interpreted as representing a latent dimension of naturalness that influenced participants' judgments and image arrangement decisions as they were rating the similarity of architectural scenes. As such, these results show that participants "see" naturalness in these architectural scenes even though they are not primed to do so in any way.

#### *Modeled Naturalness predicts similarity ratings*

The preceding analyses have established that people have consistent perceptions of what they consider to be *natural*-looking architectural scenes, and that this aesthetic quality explains a substantial proportion of variance in similarity ratings of interior and exterior architectural scenes. Another important question to consider is whether similarity ratings (Dimension 1 weights) are driven by bottom-up perceptions of naturalness, i.e. naturalistic

qualities inherent in low-level scene features. Kardan et al. (2015) demonstrated that naturalness modeled by low-level visual features provides a reliable estimate for the bottom-up perception of naturalness. Following their approach, a regression equation derived from Table 5.1<sup>55</sup> in Experiment 1 was used as the model for calculating the naturalness scores predicted by low-level visual features (Modeled Naturalness) for both sets of interior images. Dimension 1 weights were then regressed on these modeled naturalness scores. The Explicit Nature variable (calculated in Experiment 1) was added to the regression models to control for the variance in Dimension 1 weights explained by the vegetation content of the scenes.

Modeled Naturalness independently explained 73% of variance in Dimension 1 weights for Interiors A and 59% of variance in Dimension 1 weights for Interiors B, when controlling for Explicit Nature. For the exterior image sets, Modeled Naturalness was calculated using a regression equation derived from Table 5.2<sup>56</sup> in Experiment 1 and Dimension 1 weights were regressed on these predicted naturalness scores. Modeled Naturalness explained 54% of variance in Dimension 1 weights for Exteriors A and 60% of variance in Dimension 1 weights for Exteriors B, when controlling for Explicit Nature. These results suggest that the bottom-up perception of nature-like visual patterns may play an important role in driving similarity ratings of interior and exterior architectural scenes. These naturalistic low-level visual features strongly predicted image similarity scores independent of how much vegetation was present in the architectural scenes, indicating that visual qualities of the buildings depicted in the images robustly influenced perceptions of scene similarity. Results of these analyses are shown in the four tables below.

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<sup>55</sup> Naturalness = 0.452\*Scaling – 0.102\*Entropy - 0.044\*Hue + 0.118\*Sat - 0.122\*Bright - 0.106\*sdHue + 0.136\*sdSat + 0.173\*sdBright + e

<sup>56</sup> Naturalness = 0.289\*Scaling - 0.107\*Entropy - 0.016\*Hue - 0.106\*Sat + 0.066\*Bright + 0.027\*sdHue + 0.362\*sdSat + 0.227\*sdBright + e



**Table 5.3: Regression of Dimension 1 weights vs. modeled naturalness and Explicit Nature (Interiors A)**

Visual Feature	Estimate	SE	$\beta_{ST}$	<i>t</i> value	<i>P</i> value	$\eta_p^2$
Modeled Naturalness***	0.506	0.039	0.848	12.88	< .001	0.725
Explicit Nature	-1.272	1.461	-0.057	-0.87	0.388	0.012

$R^2_{adj} = 0.72$ ,  $F(2, 63) = 84.48$ ,  $P < .001$

**Table 5.4: Regression of Dimension 1 weights vs. modeled naturalness and Explicit Nature (Interiors B)**

Visual Feature	Estimate	SE	$\beta_{ST}$	<i>t</i> value	<i>P</i> value	$\eta_p^2$
Modeled Naturalness***	0.463	0.049	0.759	9.42	< .001	0.585
Explicit Nature	-3.729	1.907	-0.158	-1.96	0.055	0.057

$R^2_{adj} = 0.58$ ,  $F(2, 63) = 45.65$ ,  $P < .001$

**Table 5.5: Regression of Dimension 1 weights vs. modeled naturalness and Explicit Nature (Exteriors A)**

Visual Feature	Estimate	SE	$\beta_{ST}$	<i>t</i> value	<i>P</i> value	$\eta_p^2$
Modeled Naturalness***	0.645	0.075	0.765	8.62	< .001	0.541
Explicit Nature	-0.051	0.369	-0.012	-0.14	0.890	0.000

$R^2_{adj} = 0.57$ ,  $F(2, 63) = 43.96$ ,  $P < .001$

**Table 5.6: Regression of Dimension 1 weights vs. modeled naturalness and Explicit Nature (Exteriors B)**

Visual Feature	Estimate	SE	$\beta_{ST}$	<i>t</i> value	<i>P</i> value	$\eta_p^2$
Modeled Naturalness***	0.541	0.056	0.759	9.73	< .001	0.600
Explicit Nature	0.619	0.370	0.130	1.67	0.099	0.043

$R^2_{adj} = 0.65$ ,  $F(2, 63) = 60.94$ ,  $P < .001$

### *Nature-like patterns of scaling and contrast predict similarity ratings*

To isolate the specific importance of naturalistic patterns of scaling and contrast in predicting image similarity ratings, Modeled Naturalness was decomposed to Modeled-Naturalness-Scaling and Modeled-Naturalness-Contrast. These two variables provide quantitative estimates for two of Alexander's proposed patterns of natural structure, *Levels of Scale* and *Contrast* (Alexander, 2002). Modeled-Naturalness-Scaling represents the naturalness scores predicted by the Scaling measure, which was calculated by taking the average of the Edge Density and Fractal Dimension measures for each architectural scene. Modeled-Naturalness-Contrast represents the naturalness scores predicted by sdHue, sdSat, and sdBright, which offer approximate measures for the distribution of two different types of visual contrast throughout a scene – color contrast (sdHue and sdSat) and brightness contrast (sdBright).

**Table 5.7: Regression of Dimension 1 weights vs. naturalness scores modeled by scaling and contrast features (Interiors A)**

Visual Feature	Estimate	SE	$\beta_{ST}$	t value	P value	$\eta_p^2$
Modeled-Naturalness-Scaling***	0.701	0.073	0.713	9.55	< .001	0.595
Modeled-Naturalness-Contrast**	0.392	0.117	0.250	3.36	0.001	0.154
Explicit Nature	-1.175	1.554	-0.053	-0.76	0.452	0.009

$R^2_{adj} = 0.70, F(3, 62) = 50.55, P < .001$

**Table 5.8: Regression of Dimension 1 weights vs. naturalness scores modeled by scaling and contrast features (Interiors B)**

Visual Feature	Estimate	SE	$\beta_{ST}$	t value	P value	$\eta_p^2$
Modeled-Naturalness-Scaling***	0.600	0.082	0.628	7.31	< .001	0.463
Modeled-Naturalness-Contrast**	0.434	0.134	0.279	3.24	0.002	0.145
Explicit Nature	-3.053	1.993	-0.129	-1.53	0.131	0.036

$R^2_{adj} = 0.54, F(3, 62) = 26.51, P < .001$

**Table 5.9: Regression of Dimension 1 weights vs. naturalness scores modeled by scaling and contrast features (Exteriors A)**

Visual Feature	Estimate	SE	$\beta_{ST}$	t value	P value	$\eta_p^2$
Modeled-Naturalness-Scaling***	0.575	0.138	0.366	4.18	< .001	0.220
Modeled-Naturalness-Contrast***	0.513	0.086	0.559	5.97	< .001	0.365
Explicit Nature	0.004	0.377	0.001	0.01	0.993	0.000

$R^2_{adj} = 0.55, F(3, 62) = 27.45, P < .001$

**Table 5.10: Regression of Dimension 1 weights vs. naturalness scores modeled by scaling and contrast features (Exteriors B)**

Visual Feature	Estimate	SE	$\beta_{ST}$	t value	P value	$\eta_p^2$
Modeled-Naturalness-Scaling*	0.247	0.121	0.164	2.04	0.045	0.063
Modeled-Naturalness-Contrast***	0.503	0.057	0.689	8.80	< .001	0.555
Explicit Nature	0.712	0.365	0.150	1.95	0.056	0.058

$R^2_{adj} = 0.67, F(3, 62) = 44.12, P < .001$

The results of regressing Dimension 1 weights on these two features of Modeled Naturalness across the four sets of images are shown above. Naturalness modeled by Scaling and Contrast features explained approximately 75% of variance in Dimension 1 weights for Interiors A and 61% of Dimension 1 weights for Interiors B, when controlling for Explicit Nature, as well as 59% and 62% of variance in Dimension 1 weights for Exteriors A and Exteriors B, respectively. These results suggest that nature-like patterns of Scaling and Contrast may play an important role in driving similarity ratings of interior and exterior architectural scenes, independent of how much vegetation the scenes contain. In other words, people may unconsciously “see” these architectural patterns when arranging images of buildings even though they are not primed to do so in any way.

### **Experiment 3:**

#### **Does naturalness of buildings influence preference?**

Having established that participants “see” naturalness spontaneously (even while not necessarily aware of it) in purely architectural scenes, a third experiment was conducted to determine whether aesthetic preferences for these scenes are influenced by nature-like features of architectural design. It was predicted that people would exhibit preferences for images of buildings that were perceived as natural over artificial-looking scenes, and that low-level scene features associated with naturalness – especially scaling and contrast patterns – would substantially drive aesthetic preference ratings for both interior and exterior architectural scenes.

### **Methods**

#### *Participants*

100 American adults (63 Women, 37 men) were recruited for this experiment from Amazon’s Mechanical Turk (MTurk) to make preference ratings of the two architectural image sets. Sample size was determined by the goal of obtaining approximately 50 preference ratings per image (Kotabe et al., 2016b, 2017). Half of participants (Group 1) were assigned to rate images of interior spaces ( $n=50$ ), and the other half (Group 2) were assigned to rate images of exterior spaces ( $n=50$ ). Ages ranged from 20 to 60 years ( $M = 33.3$ ,  $SD = 9.5$ ). In terms of ethnicity, 74 participants identified as white, 5 as African American, 4 as Asian, 10 as Hispanic, 6 as Multiple Ethnicities, and 1 as Other. Income ranged from under \$10,000 per year to over \$150,000 per year ( $M = 42,000$ ,  $SD = 28,280$ ). In terms of highest educational degree attained, 4 participants reported having a postgraduate professional degree, 5 reported having a Master’s degree, 40 reported having a Bachelor’s degree, 13 reported having an Associate’s degree, 25 reported having some college education with no degree, 12 reported having a high school degree, and 1 participant reported having some high school education with no degree. Data was excluded from 4 participants who gave the same preference rating for 10 or more consecutive stimuli at least once during their individual trial, as this response pattern indicated that they were not attending to the task. All participants were compensated \$1.00 for their participation and

the experiment took approximately 10 minutes to complete. Informed consent was obtained through the Institutional Review Board (IRB) of the University of Chicago.<sup>57</sup>

### *Procedure*

Participants rated the interior and exterior image sets from Experiment 1 using the online interface of Qualtrics survey software. Group 1 participants ( $n=50$ ) were asked to rate how much they liked each interior image using a Likert scale ranging from 1 to 7, with 1 indicating strong dislike and 7 indicating strong preference. Group 2 participants ( $n=50$ ) followed the same procedure but made preference ratings for images of architectural exteriors rather than interiors.

### *Statistical analysis*

Analyses were conducted at the image level by calculating average preference ratings for each image across all participants, and by using image-level naturalness scores obtained in Experiment 1. First, preference ratings were regressed on naturalness ratings using a simple linear regression model. The next analysis examined the degree to which naturalness scores modeled by low-level visual features (Modeled Naturalness) predicted preference ratings, when controlling for high-level semantic depictions of vegetation (Explicit Nature). This analysis was accomplished by constructing regression models of preference ratings as a function of Modeled Naturalness scores (calculated in Experiment 2) and Explicit Nature scores (calculated in Experiment 1). The final analysis examined the degree to which naturalistic scaling and contrast patterns predicted preference ratings across both image sets by regressing preference ratings on naturalness scored modeled by scaling and contrast features, respectively.

## **Results**

### *Naturalness predicts preference*

The first analysis explored the degree to which the mean naturalness ratings of interior and exterior images predicted mean preference ratings. The perception of naturalness strongly predicted preference for both architectural interiors [ $R_2 = 0.70$ ,  $F(1, 118) = 275$ ,  $P < .001$ ,  $\beta_{ST} = 0.836$ ,  $t = 16.58$ ] and exteriors [ $R_2 = 0.45$ ,  $F(1, 118) = 96.1$ ,  $P < .001$ ,  $\beta_{ST} = 0.670$ ,  $t = 9.81$ ].

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<sup>57</sup> These MTurk experiments were implemented by Hiroki Kotabe, a collaborator at the University of Chicago.

These results suggest that architectural scenes with more naturalistic qualities are preferred, on average, over scenes that are perceived as more artificial. This finding extends past empirical work linking naturalness and preference (S. Kaplan et al., 1972; Kardan, Demiralp, et al., 2015) to the context of architectural scenes.

### *Modeled Naturalness predicts preference*

The next analysis investigated whether preference ratings were influenced by naturalistic low-level visual features (Modeled Naturalness) when controlling for the amount of vegetation present in the architectural scenes (Explicit Nature). To address this question, aesthetic preference ratings were regressed on Modeled Naturalness, i.e. naturalness ratings predicted by low-level visual features alone (calculated in Experiment 2). The Explicit Nature variable (calculated in Experiment 1) was also added into the regression models to control for the variance in preference ratings explained by vegetation. Linear multiple regression models were constructed, in which preference scores were plotted as a function of Modeled Naturalness and Explicit Nature for both image sets. The results of these regressions are shown in Table 5.11 and Table 5.12. For interior scenes, Modeled Naturalness explained 53% of the variance in preference ratings when controlling for Explicit Nature. For exterior scenes, Modeled Naturalness explained approximately 35% of the variance in preference ratings when controlling for Explicit Nature.<sup>58</sup> Together, these results suggest that naturalistic low-level visual patterns of architectural scenes may play an important role in generating aesthetic pleasure, and that this effect goes well above and beyond the influence of explicit natural content (i.e. vegetation) on preference ratings. In other words, participants exhibited strong preferences for the naturalistic qualities inherent in the buildings themselves.

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<sup>58</sup> The low amount variance explained by Explicit Nature in both image sets is likely due to the fact that there was relatively little vegetation present in both interior and exterior scenes, as scenes with minimal vegetation were intentionally chosen during the image selection process.

**Table 5.11: Regression of preference ratings vs. Modeled Naturalness and Explicit Nature (Interiors)**

Visual Feature	Estimate	SE	$\beta_{ST}$	<i>t</i> value	<i>P</i> value	$\eta_p^2$
Modeled Naturalness***	1.050	0.091	0.728	11.53	< .001	0.532
Explicit Nature*	8.052	3.431	0.148	2.35	0.021	0.045

$$R^2_{adj} = 0.53, F(2, 117) = 67.69, P < .001$$

**Table 5.12: Regression of preference ratings vs. Modeled Naturalness and Explicit Nature (Exteriors)**

Visual Feature	Estimate	SE	$\beta_{ST}$	<i>t</i> value	<i>P</i> value	$\eta_p^2$
Modeled Naturalness***	1.230	0.155	0.599	7.94	< .001	0.350
Explicit Nature	1.126	0.929	0.091	1.21	0.228	0.012

$$R^2_{adj} = 0.39, F(2, 117) = 39.51, P < .001$$

### *Nature-like patterns of scaling and contrast predict preference*

To isolate the specific importance of naturalistic patterns of scaling and contrast in predicting preference ratings, Modeled Naturalness was decomposed to Modeled-Naturalness-Scaling and Modeled-Naturalness-Contrast, as described in Experiment 2. These two variables provide quantitative estimates for two of Alexander's proposed patterns of natural structure, *Levels of Scale* and *Contrast* (Alexander, 2002). The results of regressing preference on these two components of Modeled Naturalness are shown in Table 5.13 and Table 5.14. The Explicit Nature variable was added into both regression models to control for the presence of vegetation in the scenes. Naturalness modeled by scaling and contrast features explained 53.5% of the variance in preference ratings for interior scenes and 31.5% of the variance in preference ratings for exterior scenes, independent of the variance explained by vegetation. Images of buildings with more scaling differentiation and greater visual contrast dispersed throughout the scene were typically regarded as more natural-looking and received higher preference ratings across both image sets. These findings support the hypothesis that naturalistic scaling and contrast patterns in architectural scenes may play a role in generating aesthetic pleasure.

**Table 5.13: Regression of preference ratings vs. naturalness scores modeled by scaling and contrast features (Interiors)**

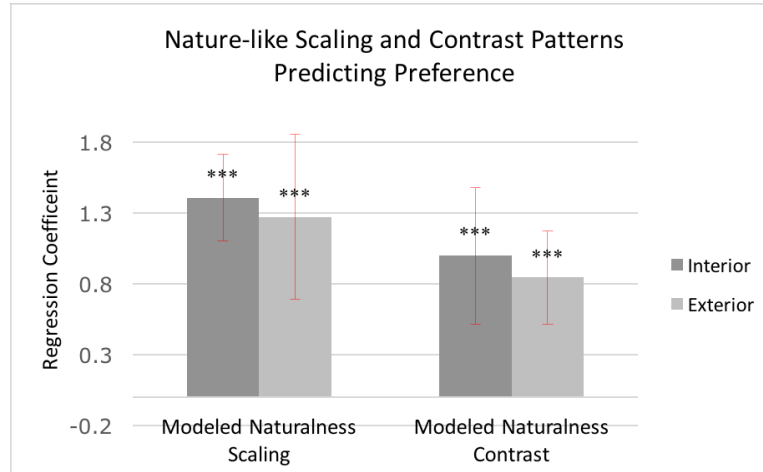
Visual Feature	Estimate	SE	$\beta_{ST}$	<i>t</i> value	<i>P</i> value	$\eta_p^2$
Modeled-Naturalness-Scaling***	1.407	0.156	0.602	9.004	< .001	0.411
Modeled-Naturalness-Contrast***	0.998	0.246	0.269	4.057	< .001	0.124
Explicit Nature*	8.685	3.472	0.160	2.502	0.014	0.051

$$R^2_{adj} = 0.53, F(3, 116) = 44.93, P < .001$$

**Table 5.14: Regression of preference ratings vs. naturalness scores modeled by scaling and contrast features (Exteriors)**

Visual Feature	Estimate	SE	$\beta_{ST}$	t value	P value	$\eta_p^2$
Modeled-Naturalness-Scaling***	1.271	0.297	0.330	4.276	< .001	0.136
Modeled-Naturalness-Contrast***	0.843	0.168	0.395	5.025	< .001	0.179
Explicit Nature	1.146	0.945	0.093	1.214	0.227	0.013

$R^2_{adj} = 0.39, F(3, 116) = 24.80, P < .001$

**Figure 5.15: Regression coefficients of regressing preference ratings on *Modeled-Naturalness-Scaling* and *Modeled-Naturalness-Contrast*. Error bars represent 95% confident intervals for coefficient values.**

In order to test whether the effects of Modeled-Naturalness-Scaling and Modeled-Naturalness-Contrast on Preference were significantly different from each other, the 95% confidence intervals of the regression coefficients (B) of these variables were estimated for interior and exterior images. B values for different variables in a linear multiple regression model are considered significantly different from each other ( $p < .05$ ) if their 95% confidence intervals overlap by less than 50% (Cumming, 2009). As can be seen in Figure 5.15, the confidence intervals for Modeled-Naturalness-Scaling and Modeled-Naturalness-Contrast appear to overlap by more than 50% for both interior and exterior image sets. The amount of overlap was estimated more precisely for interiors by calculating half of the average of the overlapping confidence intervals (0.201) and adding this value to the lower bound of the Modeled-Naturalness-Scaling confidence interval (1.095), yielding a value of 1.296. Since the upper bound B estimate for Modeled-Naturalness-Contrast of 1.490 exceeded this value (1.296), the Modeled-Naturalness-Scaling B value was not considered significantly larger than the Modeled-Naturalness-Contrast B value for interiors.

For exteriors, half of the average of the overlapping confidence intervals (0.233) was calculated and this value was added to the lower bound of the Modeled-Naturalness-Scaling confidence interval (0.677), resulting in a value of 0.910. Since the upper bound B estimate for Modeled-Naturalness Contrast of 1.179 exceeded this value, the difference between B estimates for Modeled-Naturalness-Scaling and Modeled-Naturalness-Contrast was not considered statistically significant. Therefore, the effect of Modeled-Naturalness-Scaling was not statistically significantly higher than the effect of Modeled-Naturalness-Contrast on Preference for either interior or exterior images.

### **Experiment 4: Why are natural patterns preferred?**

Having established that naturalistic design patterns consistently predict preference ratings for architectural scenes, a fourth experiment was conducted to investigate why natural patterns are preferred by examining statistical relationships between nature-like scene features and proxies for the three psychological components identified in Chapter 3 (*Fluency*, *Fascination*, and *Hygge*). This was an exploratory study (there was no initial hypothesis) designed to shed light on the more subtle aspects of psychological experience that are evoked when people view biophilic architectural scenes. The goal of the study was to see which of the three psychological components identified in Chapter 3 was most closely related to the aesthetic experience of viewing naturalistic patterns in architecture. Three ratings scales were used to operationalize these psychological components: Order (corresponding to *Fluency*), Excitement (corresponding to *Fascination*), and Comfort (corresponding to *Hygge*). These three rating scales were chosen as proxies for the three principal components because each rating scale loaded strongly on one of the components in the PCA carried out in Experiment 1 of Chapter 3. It was necessary to generate proxies for these components because the actual component names (*Fluency*, *Fascination*, and *Hygge*) did not serve as optimal anchor labels for a rating scale task, and the proxy variables were deemed easier for a participant to interpret when performing such a task.

#### *Participants*

300 American adults were recruited for this experiment from Amazon's Mechanical Turk (MTurk) to rate architectural images on Order, Excitement, and Comfort. Sample size was



determined by the goal of obtaining approximately 50 ratings per image on each rating scale (Kotabe et al., 2016b, 2017). Ages ranged from 19 to 69 years ( $M = 35.2$ ,  $SD = 10.1$ ). In terms of ethnicity, 238 participants identified as white, 21 as African American, 24 as Asian, 12 as Hispanic, 2 as Native American, 2 as Multiple Ethnicities, and 2 as Other. Income ranged from under \$10,000 per year to over \$150,000 per year ( $M = 46,300$ ,  $SD = 29,800$ ). In terms of highest educational degree attained, 6 participants reported having a Doctorate, 5 reported having a postgraduate professional degree, 24 reported having a Master's degree, 123 reported having a Bachelor's degree, 40 reported having an Associate's degree, 71 reported having some college education with no degree, 31 reported having a high school degree, and 1 participant reported having some high school education with no degree.

Participants were assigned to one of six groups ( $n=50$  per group). Groups 1 and 2 were assigned to rate images on Order; Groups 3 and 4 were assigned to rate images on Comfort; and Groups 5 and 6 were assigned to rate images on Excitement. Participants in odd-numbered groups rated images of interior architectural scenes ( $n=120$ ), while those in even-numbered groups rated images on exterior architectural scenes ( $n=120$ ). Task assignment by group number is displayed in Table 5.15 below. All participants were compensated \$1.00 for their participation and the experiment took approximately 10 minutes to complete. Informed consent was obtained through the Institutional Review Board (IRB) of the University of Chicago.<sup>59</sup>

**Table 5.15: Image-rating task assignment by group**

	Order	Comfort	Excitement
<b>Interiors</b>	Group 1	Group 3	Group 5
<b>Exteriors</b>	Group 2	Group 4	Group 6

### *Procedure*

Participants rated the interior and exterior image sets from Experiments 1 and 3 using the online interface of Qualtrics survey software. Participants in Groups 1 and 2 were asked to rate each image in response to the prompt, "How disordered or ordered does this building interior look to you?" Answer choices were presented on a standard 7-point Likert scale, with 1 indicating "very disordered" and 7 indicating "very ordered." Group 3 and 4 participants

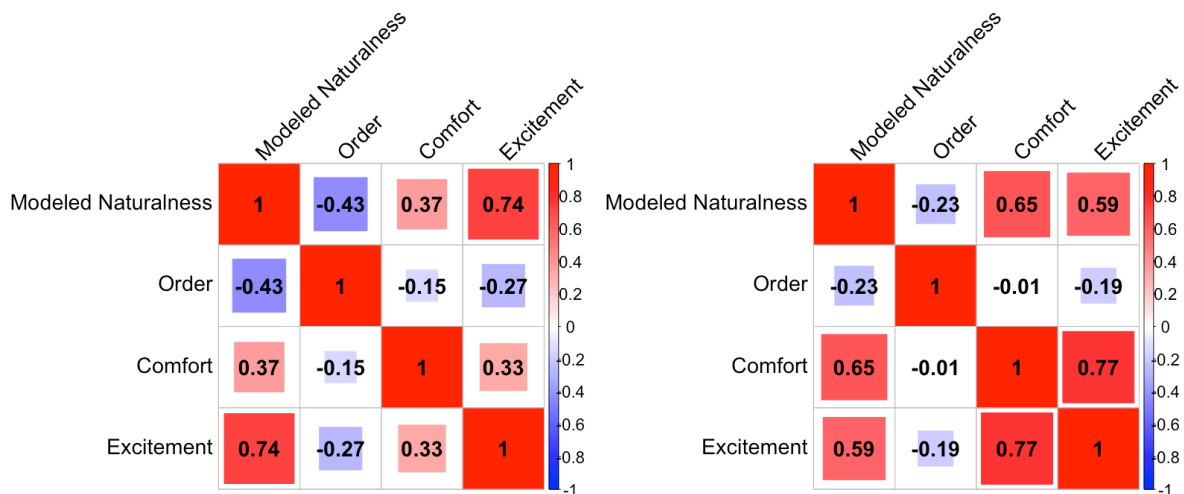
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<sup>59</sup> These MTurk experiments were implemented by Hiroki Kotabe, a collaborator at the University of Chicago.

were asked to rate each image in response to the prompt, “How uncomfortable or comfortable does this building interior make you feel?” Answer choices were presented on a 7-point Likert scale, with 1 indicating “very uncomfortable” and 7 indicating “very comfortable.” Finally, participants in Groups 5 and 6 were asked to rate images in response to the prompt, “How bored or excited does this building interior make you feel?” Answer choices were again presented on a 7-point Likert scale, with 1 indicating “very bored” and 7 indicating “very excited.”

## Results

Correlation matrices were constructed to examine relationships between naturalistic patterns of architectural scenes and the three psychological responses variables evaluated by study participants (Order, Comfort, and Excitement). Naturalistic architectural patterns were operationalized using the Modeled Naturalness variable (calculated in Experiment 2). These correlation matrixes are displayed in Figure 5.16, below.



**Figure 5.16: Correlation matrices showing correlations between Modeled Naturalness and three psychological variables (Order, Comfort, Excitement).**

For both interior and exterior scenes, Modeled Naturalness covaried significantly with all three psychological response variables. Order was found to correlate negatively with Modeled Naturalness for both interior ( $r = -0.43$ ,  $P < .001$ ) and exterior ( $r = -0.23$ ,  $P < .05$ ) scenes, indicating that scenes exhibiting more naturalistic visual patterns were perceived as more *disorderly*, on average, than scenes with more artificial-looking low-level features. However, naturalistic patterns were positively associated with more *comfortable*-looking

interior ( $r = 0.37, P < .001$ ) and exterior ( $r = 0.65, P < .001$ ) architectural scenes. Finally, Modeled Naturalness was positively associated with scenes that looked more *exciting* in the case of both interiors ( $r = 0.74, P < .001$ ) and exteriors ( $r = 0.59, P < .001$ ). With respect to the three psychological dimensions identified in Chapter 3, these results suggest that natural patterns in architecture may be preferred, in part, because they generate emotions related to *Fascination* and *Hygge*, and despite the fact that they tend to be perceived as disfluent.<sup>60</sup>

## Discussion

This chapter investigated whether subjective perceptions of naturalness are driven by objective low-level features of architectural images and examined the degree to which nature-like architectural features influence similarity evaluations and preference ratings for interior and exterior architectural scenes. The first experiment revealed that perceptions of naturalness covaried significantly with low-level spatial and color features of images and were significantly associated with two of Alexander's proposed patterns of natural structure, *Levels of Scale* and *Contrast* (Alexander, 2002), across both image sets. Image similarity scores derived from an image arrangement task in the second experiment correlated highly with subjective naturalness ratings, suggesting that people may intuitively organize and evaluate architectural images based on latent perceptions of naturalness. In other words, people utilize naturalness as a grouping method in architectural scenes spontaneously and automatically even when they are not primed to do so in any way. Results from the third experiment indicated that nature-like patterns strongly predicted preference ratings of both interior and exterior architectural scenes, supporting the hypothesis that people inherently prefer organic architectural patterns over artificial or synthetic forms. The final experiment suggested that preferences for naturalistic architectural patterns may be associated with feelings of comfort and excitement that such patterns evoke.

Results from Experiment 1 build on previous findings showing that subjective perceptions of naturalness are influenced by low-level spatial and color features for outdoor scenes (Berman et al., 2014; Kardan, Demiralp, et al., 2015), many of which had little to no built structure.

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<sup>60</sup> Disorder has consistently been found to correlate negatively with preference in previous studies (Kotabe et al., 2017), including the two experiments presented in Chapter 3 of this thesis.

Here, these findings are extended to architectural scenes, many of which had little to no vegetated content, demonstrating that perceptions of whether a building looks natural or artificial can also be reliably predicted by low-level scene features. Image statistics in the regression models independently predicted 54% of variance in naturalness ratings for interior scenes and 42% of variance for exterior scenes when controlling for the amount of vegetation visible in the scenes. Interestingly, the same three visual features (Scaling, sdSat, and sdBright) significantly predicted naturalness scores for both interior and exterior architectural stimuli. Furthermore, two of these features (Scaling<sup>61</sup> and sdSat) were previously shown to drive perceptions of naturalness in outdoor scenes (Berman et al., 2014; Kardan, Demiralp, et al., 2015). The consistency of these results suggests that certain sensory qualities associated with naturalness may transcend scene categories. In other words, visual patterns that make landscapes feel natural can potentially be reproduced in architecture, making some buildings feel as if they emerged organically from the earth.

This idea echoes the general philosophy outlined in the *Nature of Order* books (Alexander, 2002), which argue that buildings develop nature-like visual patterns when the processes by which they are constructed resemble biological growth. Although evaluating construction processes was beyond the scope of this study, Experiment 1 enabled us to measure two of these proposed nature-like patterns, *Levels of Scale* and *Contrast*, and test whether they determined subjective naturalness ratings of architectural scenes. The Scaling measure and two of the three contrast measures (sdSat and sdBright) significantly predicted naturalness ratings for both interior and exterior image sets, supporting the hypothesis that images of buildings exhibiting more *Levels of Scale* and greater visual *Contrast* tend to look more natural (Alexander, 2002).

These patterns predicted naturalness ratings even when controlling for Explicit Nature, i.e., the presence of vegetation, indicating that naturalistic visual patterns inherent in the buildings themselves were likely driving perceptions of naturalness. This finding supports the idea that perceptions of naturalness may not depend exclusively on conscious recognition of

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<sup>61</sup> In the previous study, Scaling was not directly measured. Rather, measures of Edge Density correlated positively with naturalness. However, these measures are nearly identical, given that the Scaling measure was a composite of Edge Density and Fractal Dimension, which were highly correlated across both image sets.

specific nature-related semantic content in an environment, but may also be driven by intuitive responses to abstract geometric patterns in architecture, such as scaling and contrast features, that evoke unconscious associations with the natural world (Alexander, 2002; Kellert, 2005).

The results of Experiment 1 represent an important advancement of Alexander's theory of natural structure. At various point in *The Nature of Order*, Alexander suggests that the fifteen patterns of natural structure are properties of physical space, and that many of these patterns could be objectively measured if appropriate tools were developed. However, no explicit attempts to quantify these patterns have been published. The measurement of *Levels of Scale* and *Contrast* using low-level visual features is the first scientific attempt (to the author's knowledge) to operationalize these patterns. Furthermore, the two measures of these patterns developed here were both found to correlate significantly with perceptions of naturalness. The consistent pattern of correlation across both interior and exterior image sets indicates that participants likely viewed these patterns as naturalistic, thus supporting Alexander's theoretical claims that these patterns are closely associated with perceptible patterns in nature. These results validate the method of using low-level visual features to measure these patterns and offer useful tools for researchers to test Alexander's broader claims that the patterns are associated with elevated feelings of life and wholeness.

Experiment 2 tested the perceptual saliency of the aesthetic quality of naturalness in architectural scenes by investigating whether scene similarity judgements obtained from an image-arrangement task were driven by latent perceptions of naturalness. Subjective naturalness ratings collected in the previous experiment significantly predicted over half of the variance in MDS Dimension 1 weights for both interior image sets and over two-thirds of variance in MDS Dimension 1 weights for both exterior image sets. Based on these data, participants seemed to intuitively evaluate architectural scenes according to their degree of naturalness while making similarity judgements, even though they were not prompted to evaluate the naturalness of the scenes in any way. These results build on previous work showing that people unconsciously rely on perceptions of naturalness to evaluate the similarity of outdoor scenes containing relatively little built structure (Berman et al., 2014). Here, these findings are extended to the context of man-made architecture, demonstrating

that naturalness is also an important perceptual dimension of architectural scenes containing relatively little vegetation.

Further regression analyses in Experiment 2 showed that, in all four image sets, naturalness modeled by low-level scene features (Modeled Naturalness) independently explained more than half of the variance in Dimension 1 weights when controlling for the amount of vegetation depicted in scenes (Explicit Nature). These results suggest that visual patterns inherent in the buildings themselves played an important role in driving participants' judgments of scene similarity during the image arrangement task. Furthermore, naturalistic scaling and contrast patterns explained between 59% and 75% of variance in Dimension 1 weights across the four image sets, indicating that people may be particularly attuned to these two patterns when evaluating the similarity of architectural scenes. It is important to note, however, that a large portion of variance in Dimension 1 weights was not captured by any of the independent variables included in the analysis, suggesting that people likely relied on other aesthetic scene features, in addition to natural patterns, when judging image similarity.

After establishing that people spontaneously use naturalness to organize purely architectural scenes, the third experiment tested whether people exhibit innate preferences for scenes exhibiting nature-like architectural patterns, as compared to scenes depicting spaces that look more artificial or synthetic. Results from Experiment 3 revealed that naturalness scores modeled by low-level visual features (Modeled Naturalness) independently explained 53% of variance in preference ratings for interior scenes and 35% of variance in preference ratings for exterior scenes, indicating that these patterns likely played an important role in driving preference ratings. Nature-like scaling and contrast patterns, specifically, accounted for most of the explained variance across both image sets, supporting the hypothesis that these architectural patterns may generate aesthetic pleasure by "tap[ping] into our inherent responses to the patterns, movements, light, shape, and space encountered in nature" (Kellert, 2005, p. 159).

An interesting finding that emerged across the first three experiments was that low-level visual features explained more variance in naturalness ratings, similarity perceptions, and aesthetic responses for interior scenes than for exterior scenes. One possible explanation for

this finding is that exterior scenes contained more high-level semantic scene content (e.g. sky, cars) than interior scenes, and that these visual cues contributed to aesthetic perceptions independent of the effect of low-level visual features. Such features could potentially reduce the relative amount of variance explained by low-level visual features alone. Although the regression models controlled for one high-level visual features, Explicit Nature, it is likely that other high-level scene content influenced aesthetic preference ratings above and beyond the effect of Explicit Nature, and that this variance was not captured in the regression models. An alternative explanation is that the specific naturalistic patterns measured in this study (including Scaling and Contrast features) are relatively more salient for aesthetic perceptions of interior scenes, while other low-level features not captured in these regression models (e.g. local symmetries) are more salient in the context of exterior scenes. Finally, the slight differences in variance explained for interior vs. exterior scenes may simply be due to random variation between the two image sets. Whatever the reasons for this discrepancy may be, the more notable overall result may actually be the high degree of consistency between the two image sets in terms of the amount of variance in aesthetic perceptions explained by naturalistic visual patterns.

In the final experiment, correlations were examined between naturalistic visual patterns (Modeled Naturalness) and proxies for the three salient psychological dimensions identified in Chapter 3 of this dissertation: Order (*Fluency*), Comfort (*Hygge*), and Excitement (*Fascination*). Modeled Naturalness was found to co-vary significantly with feelings of comfort and excitement, suggesting that naturalistic architectural patterns might be preferred, in part, because they evoke emotions related to the *Fascination* and *Hygge* components of architectural experience that were discussed at length in Chapter 3.

Interestingly, Modeled Naturalness was also found to be negatively associated with perceptions of order. Given that order often correlates positively with aesthetic preference (Kotabe et al., 2017; Reber et al., 2004; see also Figure 3.3 and Figure 3.6 in Chapter 3), this finding suggests that naturalistic patterns in architectural scenes may be preferred despite the fact that they are perceived as disorderly. This interpretation is consistent with the *nature trumps disorder* hypothesis proposed by Kotabe et al. (2017), which suggests that “aesthetic preference for nature is more powerful than aesthetic aversion to disorder, thus natural scenes can be disorderly yet aesthetically preferred” (Kotabe et al., 2017, p. 3).

The results of Experiment 4 build on Alexander's thesis about the experiential benefits of exposure to naturalistic patterns in architecture. A central idea in Alexander's *Nature of Order* books is the concept of 'living structure,' which he describes as a fundamental property of architecture that is associated with the presence of nature-like geometric patterns in the physical structure of a building. Two of these fifteen patterns (*Levels of Scale* and *Contrast*) were operationalized and tested in the present series of experiments. According to Alexander's theory, buildings and architectural spaces that exhibit these nature-like visual patterns can be said to express a higher degree of 'living structure' than spaces that lack these patterns. He proposes, furthermore, that the relative presence of this quality in a given environment can fundamentally influence how we experience that place. We tend to feel more connected to places with a higher degree of 'living structure,' and more disconnected from places that lack this quality. In turn, built spaces that exhibit more 'living structure' often make us feel more comfortable, more whole, and more free to be our "authentic" selves (Alexander, 2002). 'Living' places, he asserts, generate deep feeling in us, and consequently make us feel more alive. These are some of the foundational claims of the *Nature of Order*.

Although Alexander offers a rather complex analysis of the geometric patterns underlying 'living structure,' his approach to describing the feelings that these patterns engender have been criticized for appearing to be largely observational and subjective (Saunders, 2002). His conclusions about the effects of 'living structure' on human experience are mostly based on his own observations but have never really been empirically tested. Furthermore, his *magnus opus* has received a fair amount of criticism for relying on somewhat broad and, at times, vague descriptions of the types of "feelings" that 'living structure' generates in people, and for claiming that these "feelings" are universal, when in fact the theories he presents are based only in his own observations and lived experiences (Saunders, 2002).

One of the primary aims of the experiments conducted in Chapter 4 was to address some of these limitations of Alexander's original work. These limitations have been addressed in two ways. First, empirical evidence (beyond Alexander's own claims) has now emerged linking two of Alexander's proposed patterns of 'living structure' (Scaling and Contrast) to key psychological response measures. Both of these naturalistic patterns were found to be significant predictors of similarity evaluations and aesthetic preference ratings of architectural scenes. Specifically, Scaling and Contrast-related measures were found to



explain 53% of variance in preference ratings for interiors and 32% of variance in preference ratings for exteriors. The fact that these statistical patterns emerged in a random sample of 100 individuals strengthens Alexander's argument that many people "see" these patterns (based on the MDS experiment results) and respond positively to them (based on the preference results). Thus, these experiments help move Alexander's argument about the universality of human perceptions of natural patterns beyond the realm of one architect's theoretical claims and into the arena of empirically-testable scientific hypotheses.

Secondly, this chapter builds on Alexander's work by identifying more nuanced experiential dimensions of what Alexander describes as the "feelings" generated by natural patterns and 'living structure.' Specifically, the results of Experiment 4 demonstrated that natural patterns (operationalized as Modeled Naturalness) were significantly associated with feelings of comfort (interiors:  $r = 0.37$ ; exteriors:  $r = 0.65$ ) and excitement (interiors:  $r = 0.74$ ; exteriors:  $r = 0.59$ ). Furthermore, natural patterns were negatively correlated with the perception of order in architectural scenes. These findings offer further insight into the nature of the "feelings" generated by natural patterns in architecture, which Alexander had previously described somewhat more vaguely as experiences of "aliveness" and "wholeness." Perhaps these feelings have something to do with the experience of feeling simultaneously excited and comfortable in naturalistic built spaces. In addition to the association discovered between natural patterns and the "comfort" measure, it's also interesting to note that Alexander's descriptions of "aliveness" and "wholeness" overlap significantly with the literature on the experience of *hygge* (Wiking, 2017; Linnet, 2012; see "discussion" section of Chapter 3). Although Alexander never specifically discusses *hygge* in his work, this concept seems to align closely with the types of spatial experiences that he aspires to create in his buildings and to promote in his architectural writing. This connection would be an interesting topic of investigation in future studies.

The idea that humans are innately drawn to nature-inspired architectural forms dates back several centuries. Immanuel Kant believed that the most beautiful human creations look as if they emerged organically from the earth, because they reflect the artist's intuitive understanding of nature's underlying order (Kant, 2001; originally published in 1790). Philosopher John Ruskin later wrote that "whatever is in architecture fair or beautiful is imitated from natural forms" (Ruskin, 1849, p. 71). Extending these ideas to the scientific

realm, contemporary proponents of biophilic design often contend that humans have developed innate affinities for naturalistic forms in their surroundings over the course of evolutionary history (Joye, 2007b; Salingaros, 2007; E. O. Wilson, 1984; E. O. Wilson & Kellert, 1995), and that nature-inspired architectural features may foster important psychological benefits (Alexander, 2002; Joye, 2007a; Kellert, 2005; Salingaros, 1998).<sup>62</sup> The experiments presented here offer among the first empirical evidence that naturalistic patterns in architecture may be inherently preferred over synthetic forms and suggest that the *biophilia* phenomenon may extend into the built environment. By quantifying two low-level patterns characteristic of naturalistic architecture – *Levels of Scale* and *Contrast* – this study also paves the way for future researchers to investigate whether variations in these patterns might enhance mood, cognitive functioning, or other aspects of psychological experience.

This research also provides useful tools for architects wishing to incorporate biophilic design features into the built environment. The two nature-like patterns that were tested here – *Levels of Scale* and *Contrast* (Joye, 2007b, p. 323) – can easily be manipulated in architectural design schemes. They are non-prescriptive, as they do not require adherence to a particular architectural style and can be adapted to many design and research contexts. The results of these experiments also highlight the importance of investigating how Alexander’s other proposed patterns of natural structure (Kellert, 2003, p. 36) and adaptive construction processes (Alexander, 2002; Joye, 2007b; Kellert, 2005; Salingaros, 2007) might impact other aspects of psychological experience, compared to more conventional approaches to architectural design and construction. These questions could be addressed in future studies that evaluate psychological and behavioral responses to varying design patterns in real or virtual environments.

## Limitations

Images of buildings were used as stimuli for these studies in order to isolate scene features related to visual perception and to expose participants to a wide variety of architectural spaces within a reasonable timeframe. However, using two-dimensional stimuli may limit the

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<sup>62</sup> Kellert, for instance, writes that “organic qualities of light, color, material, texture, shape, and form that have been symbolically borrowed from the natural world... grip the human imagination, communicating a subtle connection to the natural environment, even when the origin of our feelings remains obscure” (Kellert, 2005, p. 159)

generalizability of these findings to three-dimensional built spaces. This chapter also focused on visual perception of naturalistic patterns in architecture. It was therefore impossible to make inferences about the contribution of nonvisual sensory features of architectural spaces to perceptions of naturalness and preference, which are likely to be substantial.

Furthermore, it is important to recognize the limitations of the approach taken here to quantifying the *Levels of Scale* and *Contrast* patterns. These patterns were originally highlighted in descriptive rather than quantitative terms in the work by Alexander (2002). Here, these patterns were quantified using low-level visual features. However, alternative approaches to interpreting and measuring them could potentially yield different results. It is also likely that other features (both low-level and semantic) of architectural scenes, in addition to naturalistic patterns, contributed to participants' similarity ratings and aesthetic judgments. Although testing these variables was beyond the scope of the present chapter, the author intends to investigate the role of other variables in future studies.

In Experiment 4, it was necessary to use proxies for the three principal components identified in Chapter 3 because the actual component names (*Fluency*, *Fascination*, and *Hygge*) did not serve as optimal anchor labels for a rating scale task. Other proxy variables were also considered as rating scales for this experiment, including "organization" for PC1 (*Fluency*), "interest" and "complexity" for PC2 (*Fascination*), and "personalness" and "hominess" for PC3 (*Hygge*). "Order," "excitement," and "comfort" were chosen as the three proxy variables for this experiment because of they were deemed the most straightforward rating scales to interpret for each component. However, it is possible that the choice of different rating scales would have yielded different statistical relationships with Modeled Naturalness.

Another important limitation of Experiments 2-4 was the large amount of variance that remained unexplained by Modeled Naturalness in similarity evaluations, preference ratings, and ratings of order, comfort, and excitement. Although Modeled Naturalness was found to be a significant predictor of many of these dependent variables, it is likely that many other aesthetic features also contributed to participants' perceptions and ratings of these architectural images. These variables likely include building age, enclosure, windows, ceiling height, building height, furniture, cleanliness, and perceptible semantic scenes features like cars and street signs, to name just a few. It would be of interest to test interactions between

some of these other environmental variables and naturalness in future studies. Finally, the dependent variables studied in these experiments did not directly test the psychological benefits of naturalistic patterns in buildings, which is a common claim in the literature (Alexander, 2002; Salingaros, 2007; Kellert, 2005). Future studies could utilize tests of cognitive function, such as working memory performance, to address more directly whether biophilic features of architecture offer measurable benefits to mental health.

### **Conclusion**

These experiments attempt to operationalize the aesthetic quality of naturalness in the built environment. Evidence is presented suggesting that latent perceptions of natural patterns inherent in low-level visual features, such as Scaling and Contrast, may influence similarity evaluations and preference ratings of architectural scenes. Furthermore, nature-like architectural patterns are shown to be associated with feelings of comfort and excitement, despite being perceived as disorderly. This evidence supports a wealth of theoretical work suggesting that humans may be innately attuned to biophilic sensory features of the built environment. By identifying specific spatial and color patterns that are perceived as more natural, and which can easily be manipulated in architectural design, this research empowers architects with flexible tools for designing more biophilic spaces and enables researchers to test whether nature-like architectural features might contribute to restorative psychological experiences.

## Summary and Conclusions

This dissertation set out to advance our understanding of how aesthetic features of architectural design influence how we perceive buildings and feel in them. Chapter 1 reviewed past research on wellbeing in the built environment and highlighted the gaps in the literature that motivated this project. The evidence presented in that chapter suggested that holistic qualities of our physical surroundings, such as perceived attractiveness, may impact wellbeing more than any single design variable considered in isolation. However, the scientific research to date linking aesthetic features of the built environment to psychological response variables has been limited. To address this gap in knowledge, this research aimed to identify the key neural and psychological mechanisms underpinning architectural experiences and to improve how we measure aesthetic features of the environment.

Chapter 2 explored the neural underpinnings of architectural experience and outlined the *aesthetic triad* model, which represents the first neuroscientific framework for architectural encounters. According to this model, three large-scale neural networks generate aesthetic experiences in the built environment: sensorimotor, emotion-valuation, and knowledge-meaning systems. Architecture creates multisensory experiences by engaging visual, auditory, olfactory, and somatosensory networks. These sensory experiences, in turn, elicit motor responses such as approach and avoidance behaviors and trigger emotional responses like excitement, pleasure, and fear. Finally, memories and value judgements shaped by past experiences and education modulate individual differences in architectural experiences via knowledge-meaning systems. These top-down cognitive processes can at times inhibit or magnify the emotional and motor responses generated by bottom-up sensory processes.

This tripartite model offers a useful framework for future researchers interested in advancing the neuroscience of architecture. For instance, the model can be used to frame specific research questions, such as how specific visual patterns or acoustic design strategies might modulate neural responses related to sensory perception or emotion. However, the *aesthetic triad* is not intended to be a final model, but rather an initial framework that can be refined and improved through the advancement of both empirical and theoretical work on the neuroscience of architecture. This field is in its early stages, and additional neuroscientific research using architectural stimuli will be needed to develop a more nuanced understanding

of how specific neural systems respond to specific features of architectural design. Whether these biological insights can help inform architectural design strategies that promote positive mental health remains to be seen.

A pair of experiments was presented in Chapter 3 investigating the latent dimensions of psychological responses to architectural scenes. The chapter began with a review of sixteen semantic differential scales representing diverse aspects of architectural experience. Participants then rated images of architectural interiors on these scales, and a principal components analysis (PCA) was carried out on the data. This analysis revealed three psychological components that explained 90% of the variance in the ratings: *fluency* (the ease with which one organizes and comprehends an architectural scene), *fascination* (the degree to which a scene engages the observer and generates interest), and *hygge* (how warm and personal the interior scene feels). Whereas *fluency* and *fascination* are well-established psychological dimensions for assessing natural landscapes and visual art, *hygge* emerged as a new dimension in relation to architectural scenes.

Importantly, response variables related to all three dimensions of the *aesthetic triad* loaded on each of these three psychological components, suggesting that each component may potentially involve multimodal processing in the brain. Component scores along each of the three psychological dimensions were also sensitive to three basic aesthetic features of the architectural images: Ceiling Height, Enclosure, and Curvature. These design variables had a particularly significant effect on *fascination* scores in both studies. Furthermore, the enclosure variable had the strongest and most consistent effect in modulating *fluency*, *fascination*, and *hygge* scores. These three psychological dimensions offer a simple yet nuanced framework for mapping aesthetic responses to images of interior architectural spaces. While certainly not exhaustive, this framework enables designers and researchers to think beyond vague concepts of beauty and preference when assessing the complex mental states that people experience while viewing architectural scenes.

It is crucial to note several limitations of the studies presented in Chapter 3. As previously mentioned, using architectural images as stimuli may limit the generalizability of findings to three-dimensional spaces, since static two-dimensional images lack depth cues and remove the observer from the context of the whole building. Some of these limitations can be

addressed by using virtual simulations of architecture in future research. The author is currently conducting a follow-up study to these experiments investigating psychological responses to three-dimensional virtual rooms that vary on the same three architectural parameters as the images used in the study (Ceiling Height, Enclosure, and Curvature). While this interface enables greater visual immersion and navigation through architectural spaces, there are also limits to virtual representations of architecture, including the inability to experience virtual buildings through sound, smell, and touch. As such, real buildings will likely remain the gold standard for the foreseeable future in experimental work on the psychology of architecture. However, architectural images and virtual spaces remain a useful starting point for generating hypotheses that can then be tested in actual buildings.

There were also limitations to the psychological response measures tested in this study. The sixteen response variables chosen did not exhaustively capture all aspects of psychological experience in response to architectural scenes, but time and funding limits restricted the numbers of variables that could be included in the experiments. Future studies could build on this work and test additional response measures relevant to the built environment, such as fear and awe. Such studies would also benefit from pairing self-report response data with behavioral measures, latent perceptual measures (like the image arrangement task presented in Chapter 5), and with physiological data, such as galvanic skin response (GSR) tests, blood cortisol tests, and neuroimaging. In fact, a follow-up neuroimaging study was carried out linking the psychological response data collected in Experiment 1 of Chapter 3 with fMRI data that measured participants' (n=18) neural responses while making beauty and approach-avoidance judgements of the same set of architectural images. I did not include this study in the main body of the dissertation because the analysis was primarily conducted by one of my colleagues and falls outside of my area of expertise. However, a very basic summary of the results of this experiment can be found in Appendix A.

The final two chapters of the dissertation investigated psychological responses to nature-like patterns in the built environment. Chapter 4 offered a theoretical introduction to theory of natural structure (Alexander, 2002), which proposes that nature-like patterns in architecture induce healthy behaviors and psychological experiences. In Chapter 5, image statistics were used to quantify two patterns of natural structure in architectural scenes, *Levels of Scale* and *Contrast*, and psychological responses to these patterns were measured. As predicted, scenes

exhibiting greater *Levels of Scale* and more intense *Contrast* patterns were perceived as more natural. Furthermore, these naturalistic patterns significantly predicted evaluations of scene similarity (derived from an image arrangement task) and aesthetic preference ratings for both interior and exterior images, even when controlling for the amount of vegetation depicted in the scenes. These studies contribute to the extensive *biophilia* literature suggesting that humans may be innately attuned to nature-like sensory features in the built environment, and that biophilic design features may be preferred over synthetic-looking architectural forms.

Results of the final experiment in Chapter 5 offered more nuanced insight into why people might be attracted to biophilic features of architecture. Naturalistic visual patterns were found to be positively associated with feelings of comfort and excitement and negatively associated with perceptions of order. These results complement the experimental results of Chapter 3, in which naturalness loaded positively on the *Hygge* component and negatively on the *Fluency* component in both PCA analyses (the original and the replication). However, naturalness loaded negatively on the *Fascination* component in Chapter 3, despite correlating positively with its proxy (Excitement) in Chapter 5. This discrepancy illustrates how relationships between environmental features and psychological responses can vary somewhat depending on the stimuli, participants, and experimental design. In other words, the external validity of Experiments 3 and 5 (i.e., whether or not these results are replicable in other stimulus sets, participant groups, and experimental contexts) remains to be tested. It is possible, for instance, that studies of specific building typologies (like hospitals) may yield a different clustering of psychological dimensions than the three general groupings identified for the diverse stimulus set of Chapter 3. Collectively, however, these results offer new insights into the psychological implications of *natural structure* (Alexander, 2002) and biophilic architectural design.

The image statistics outlined in Chapter 5 offer many advantages for measuring aesthetic features of architectural scenes compared to more simplistic environmental measures – such as the Ceiling Height, Enclosure, and Curvature variables used in Chapter 3 – because they capture far more of the variance in the complex visual properties that people actually perceive when they view architectural scenes. In other words, image statistics quantify the visual dimension of architectural scenes more holistically than many of the isolated



environmental variables tested in previous studies on the psychology of architecture. This method of architectural analysis represents a promising response to the challenge issued by wellbeing researchers “to develop robust, quantitative ways of measuring the design qualities that matter, at the human scale” (Cooper & Burton, 2014, p. 666). This novel method of image analysis is highly relevant to future research as a tool for quantifying aesthetic qualities of the built environment.

However, there are also important limitations to consider with regard to this method. Image statistics cannot capture nonvisual sensory properties of architectural spaces, and they can only be applied to photographs of isolated parts of buildings, although analysis of multiple photographs of the same space could potentially yield more comprehensive analyses of a building’s holistic visual features. Furthermore, there are many possible forms of image analysis, but some of these measures, such as Fourier spectrum slope (see for instance D. J. Graham & Field, 2007), describe such complex mathematical properties of images that they are not particularly useful for the purposes of architectural design. For that reason, the studies in this thesis only relied on image statistics that could be easily manipulated by designers and that were intuitively linked to existing architectural theories (i.e. Alexander’s theory of natural structure).

It is also important to note that the experiments in Chapter 5 tested Alexander’s theory in a limited way. Only two of the fifteen proposed patterns of natural structure were quantified using image statistics, and these statistics served only as mathematical proxies for the rather complex descriptions of these patterns presented in the *Nature of Order* books (Alexander, 2002). Some of the thirteen other patterns, such as *Local Symmetries* and *Echoes*, could potentially be quantified in future studies using other low-level image features.<sup>63</sup> Others might defy empirical measurement altogether. As described in Chapter 4, the theory of natural structure also emphasizes how adaptive construction processes yield naturalistic patterns in buildings. Future studies could attempt to operationalize construction processes (rather than static visual patterns) as an independent environmental variable in order to see how such processes influence psychological experiences in the built environment. For

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<sup>63</sup> For instance, a recently described measure of self-similarity (Mallon et al., 2014) could serve as a useful proxy for Alexander’s proposed *Echoes* pattern.

instance, one could compare psychological and behavioral responses to houses built predominantly by hand compared to machine-made homes (e.g. pre-fabricated homes). It would also be fruitful to evaluate the experiential impact of some of the homes Alexander built, which were created using adaptive construction techniques described in books 2 and 3 of *The Nature of Order* (Alexander, 2002), compared to houses built from the more conventional template of static blueprints. However, evaluating construction processes was beyond the scope of this thesis.

Finally, there were limitations to the psychological variables measured in Chapter 5, which tested six response variables (naturalness, similarity, preference, order, comfort, and excitement) in response to low-level visual features of architectural scenes. Although some of the literature reviewed in Chapter 1 suggested that aesthetic preference in the built environment correlates with wellbeing, this link was not directly tested in the thesis. This potential connection could be addressed in future studies by investigating whether the environmental variables (e.g. natural patterns) and psychological dimensions (Fluency, Fascination, and *Hygge*) identified in this thesis influence long-term measures of occupant wellbeing.

Despite these limitations, the chapters of this thesis have important implications for academic research and environmental design. The literature review in Chapter 2, for instance, highlights the dearth of research to date on how non-visual sensory features contribute to the perception of architectural spaces. This is an important gap in knowledge that cognitive scientists could help address, for instance, by exploring how variations in acoustics, smell, and texture influence occupants' aesthetic experiences in buildings. Chapter 3 suggested that people may be particularly sensitive to how cozy and personal a building feels, as described by the Danish concept of *hygge*, and Chapter 5 proposed that this experiential dimension may mediate preferences for biophilic architecture. However, *hygge* has received relatively little attention in architectural research and is hardly mentioned in the biophilia literature.

Future studies could investigate potential relationships between natural architectural patterns and experiences of *hygge* in the built environment. Participants could be placed in rooms that vary in the related presence of natural patterns (as measured by the image statistics used in Chapter 5), and researchers could observe social behaviors of participants in

these rooms and assess self-reported measures of comfort and *hygge*. Such studies could be carried out in Denmark, for instance, where *hygge* is a familiar concept to most citizens, and where greater cultural emphasis is placed on this experiential quality than in other Western countries like England or the United States.

The evidence presented in Chapter 5 supports a wealth of previous research suggesting that people are instinctively attuned to nature-like patterns in their surroundings. However, synthetic shapes continue to dominate many of today's urban landscapes, and biophilic architecture remains at the periphery of contemporary property development. It may be fruitful if architects and planners start to weigh naturalness more in their design decisions, and these studies provide some tangible ways in which this quality can be manipulated in low-level visual patterns.

For example, sleek lines and flat, undifferentiated surfaces continue to define the design standard of many contemporary hospitals in the United States, and patients perceive many of these spaces as feeling cold, sterile, impersonal, and artificial. While some efforts to introduce plants and artwork into the wards have been successfully implemented, hospital designers should also consider introducing more Scaling and Contrast into the design of the architectural structure itself in order to make these environments feel more natural and comfortable. This could be achieved in by a variety of methods, for instance, by introducing natural materials such as wood and clay into the structure of hospital buildings, or by adding more detail and ornament to the existing synthetic materials that are more commonly used.

One important question to consider is how much Scaling/Contrast is sufficient to improve occupant experience. At what point might adding too much Scaling/Contrast lead to excessive visual complexity and sensory overload? The intention of these studies is not to suggest that there is a universally-applicable "prescription" for an "optimal" amount of Scaling/Contrast in architecture. Rather, designers could vary these patterns in schematic renderings of hospital spaces before they are built and could then adapt the design based on feedback from prospective occupants of the building (e.g. clinicians and patients). These features could even be manipulated in virtual environments, and occupants could give feedback on their experiential responses to the three-dimensional renderings of these patterns in the virtual environment. This feedback could then be used to inform future iterations of the design in

order to determine the appropriate amount of Scaling, Contrast, or any other aesthetic feature to implement in a space based on the specific context and occupant needs identified.

Importantly, the experiments in Chapter 5 tested some of the key theoretical claims outlined by Alexander (2002). Two of Alexander's proposed patterns of natural structure, *Levels of Scale* and *Contrast*, were found to be perceived as natural-looking properties of buildings, for both interior and exterior stimuli. The successful validation of these two "natural" patterns with empirical methods supports Alexander's hypothesis that these may be objectively-measurable properties of physical space, and that people exhibit strong agreement that these patterns look "natural." Furthermore, Alexander's assertion that people intuitively see these patterns was further supported by the findings of Experiment 2, in which nature-like Scaling and Contrast patterns were found to explain more than half of the variance in similarity ratings (MDS Dimension 1) across four sets of interior and exterior images. These results suggest that participants may be aware of these patterns when evaluating architectural scenes, and that the patterns may influence evaluation decisions, even when participants are not prompted to identify them. The subsequent experiments demonstrated that these patterns predicted scene preference ratings and correlated strongly with comfort and excitement evaluations. These results align with Alexander's hypothesis that patterns of natural structure may invoke positive psychological responses when experienced in architectural scenes.

These hypotheses – that humans can, in a sense, create "nature" in architectural design, and that natural architecture fosters positive psychological and emotional responses – provide an important theoretical bridge between biophilia research and architectural design. However, they have never been tested empirically. Chapter 5 represents the first experimental attempt to test Alexander's pioneering hypotheses. It is the author's hope that these studies may generate greater interest in theories that, up to the present, have been largely overlooked by architects and environmental psychologists alike. Alexander's early books, including *A Pattern Language* (Alexander, 1977) and *A Timeless Way of Building* (Alexander, 1979), were considered foundational texts in American and European architecture schools throughout the 1980's. By contrast, *The Nature of Order* (Alexander, 2002) has received little attention in architectural education and remains relatively unknown among both practitioners and researchers, despite being regarded as his magnum opus by some scholars.

What are the implications of these studies for design and research? First, the successful measurement of two natural patterns here suggests that it may also be possible to measure some of the remaining thirteen patterns using empirical methods. However, some of the patterns are quite qualitative in nature and may defy empirical measurement. Secondly, the finding that two of these patterns correlate with salient psychological responses such as aesthetic preference, comfort, and latent similarity evaluations suggests that further research should be conducted to test the implications of these fifteen patterns for psychological experience and wellbeing. Other aspects of psychological and social experience should be considered as dependent variables, including subjective wellbeing and social-behavioral measures (see Appendix C for some examples). Future studies should also consider how psychological responses to these patterns might change in more immersive contexts such as real buildings and virtual spaces, compared to two-dimensional images.

It's also important to emphasize that there are some groundbreaking concepts presented in *The Nature of Order* outlining novel design processes required to create natural structure in architecture. While a detailed analysis of these processes is beyond the scope of this thesis, the general idea is that building design and construction should be integrated into one adaptive process in which buildings are designed and constructed following a series of structure-preserving transformations resembling processes of biological growth (Alexander, 2004). These methods have been tested in dozens of Alexander's own real-world construction projects throughout the world (see examples in *The Nature of Order, Book 3: Vision of a Living World*). However, the pioneering approach to architectural design and construction outlined in *The Nature of Order* has not received serious consideration from architectural schools. The results of these studies may motivate leaders in architectural education to take Alexander's ideas more seriously. Adopting his approach at the institutional level could represent a paradigm shift in architectural training and practice.

As a whole, this thesis builds on previous research showing that aesthetic features of the built environment can meaningfully influence how we perceive buildings and feel in them. Chapter 1 illustrates the important link between environmental aesthetics and wellbeing. Chapters 2 and 3 then outline novel frameworks for measuring acute psychological responses to architectural design. Finally, Chapters 4 and 5 describe and test some of key aspects of Alexander's theory of natural structure, which has important implications for biophilia

## SUMMARY AND CONCLUSIONS

research and wellbeing-focused architectural design. Collectively, this work represents a small step towards improving the spaces that surround us for the majority of our lives.

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# Appendix A: Supplementary materials for Chapter 3

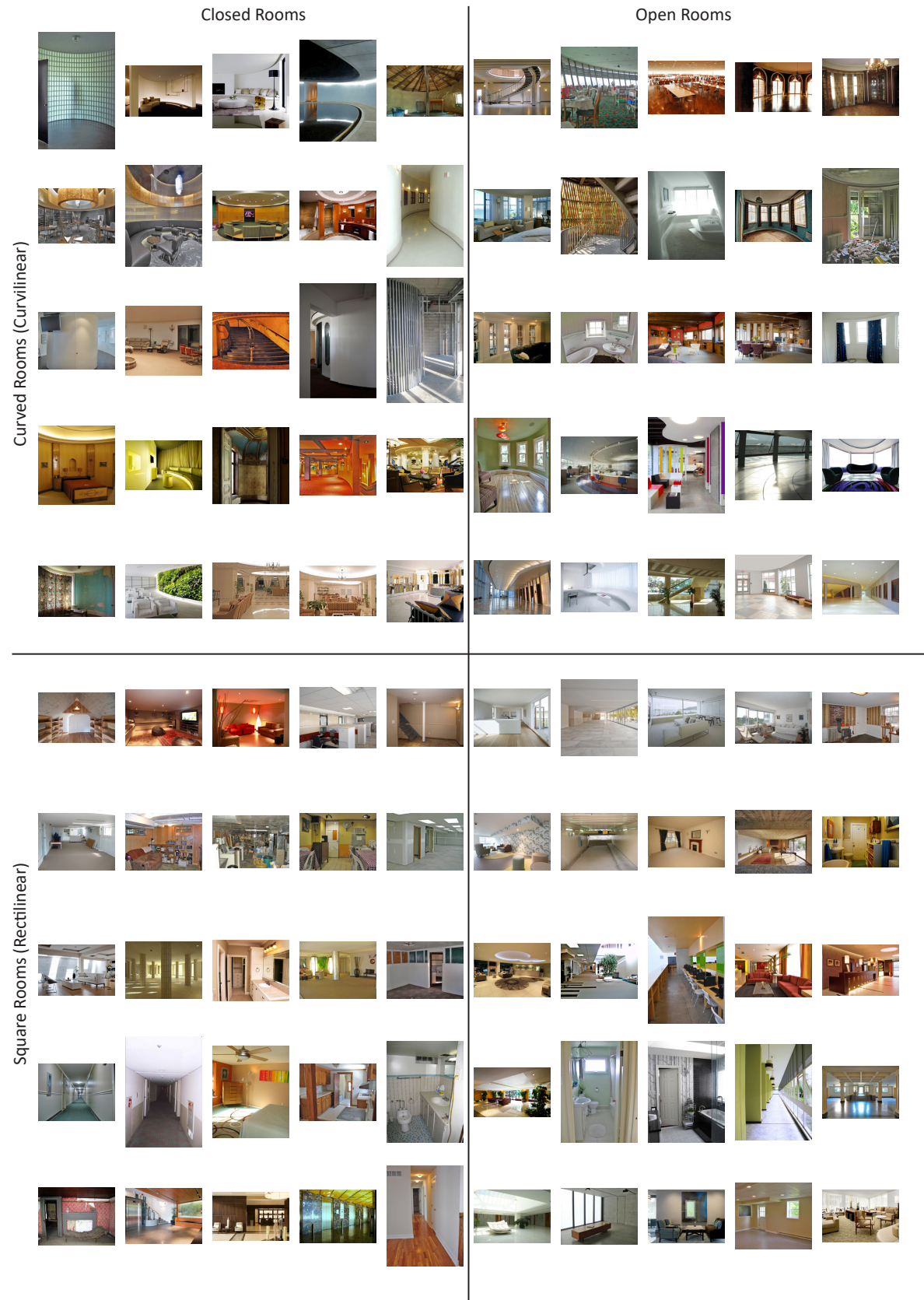


Figure A1: Experimental stimuli (low ceilings)



# APPENDIX A

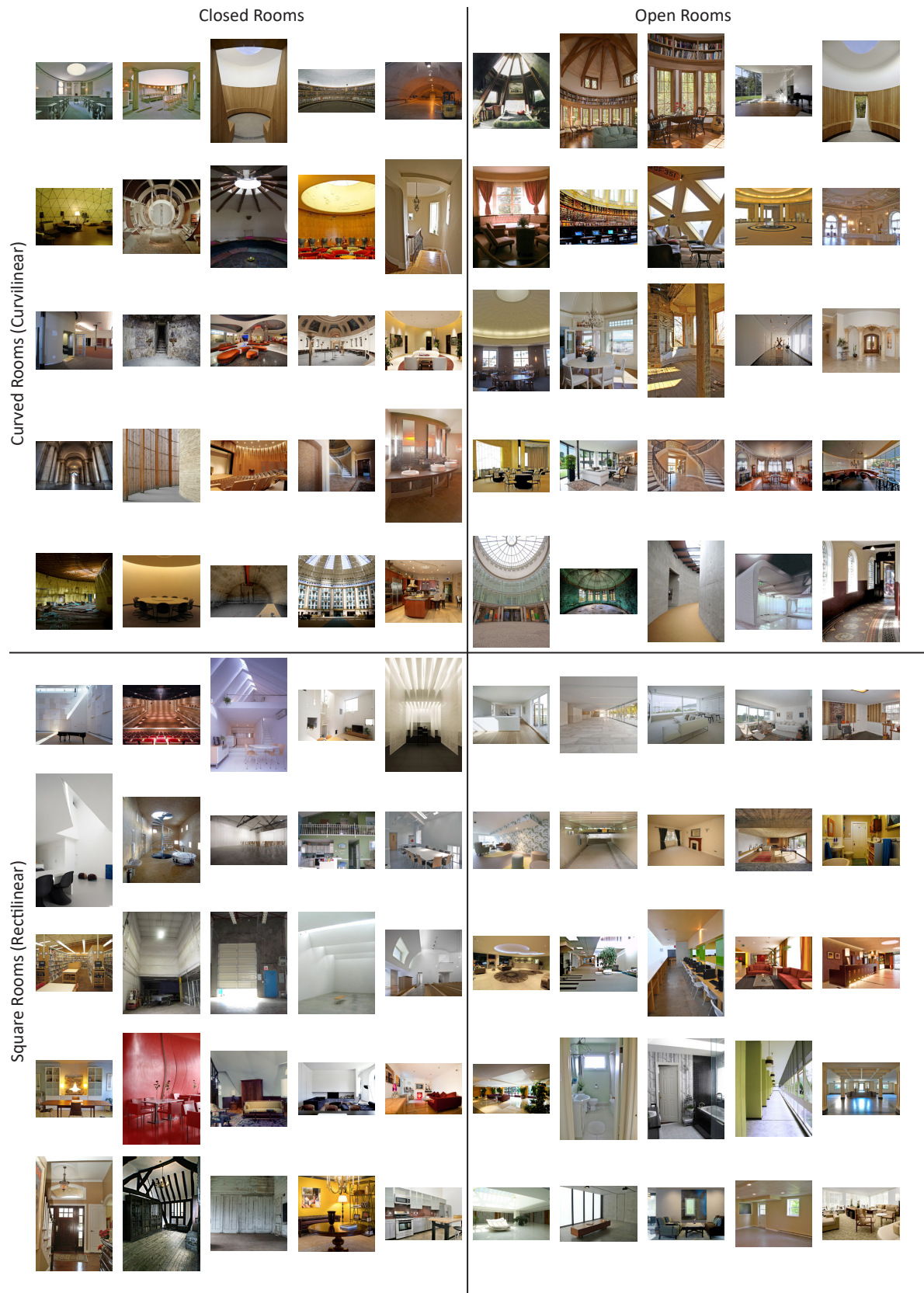


Figure A2: Experimental stimuli (high ceilings)

## Neural correlates of Fluency, Fascination, and Hygge

In a follow-up study to the work presented in Chapter 3, participants ( $n=18$ ) made beauty judgments and approach-avoidance decisions of interior architectural scenes ( $n=200$ ) while in the fMRI scanner. Parametric analyses were carried out to see if the three principal components derived from the behavioral data in Experiment 1 activated specific neural regions for each task (beauty judgements vs approach-avoidance decisions). The results of these analyses are shown below. Each principal component was significantly associated with neural activity in a distinct region of the visual cortex. PC1 (Fluency) covaried significantly with the right precuneus and left inferior occipital gyrus, but only for the task in which participants made beauty judgements. PC2 (*Hygge*) was associated with significantly greater activation in the left cuneus for both the beauty judgement and approach-avoidance tasks. Finally, PC3 (Fascination) covaried significantly with neural activity in the right lingual gyrus for both tasks. These results suggest that neural responses in visual cortices associated with Fascination and *Hygge* are task-invariant, whereas responses related to Fluency are evoked specifically when people judge architectural images on beauty.

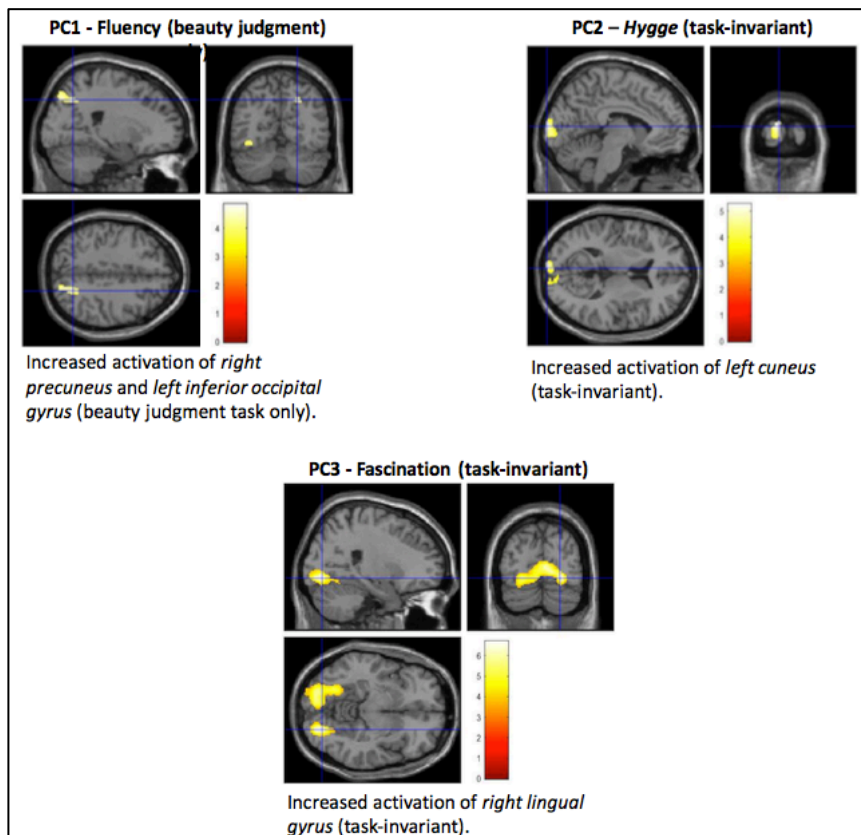


Figure A3: Neural correlates of 3 psychological dimensions derived from PCA in Chapter 3, Experiment 1.



## Appendix B: Supplementary materials for Chapter 5

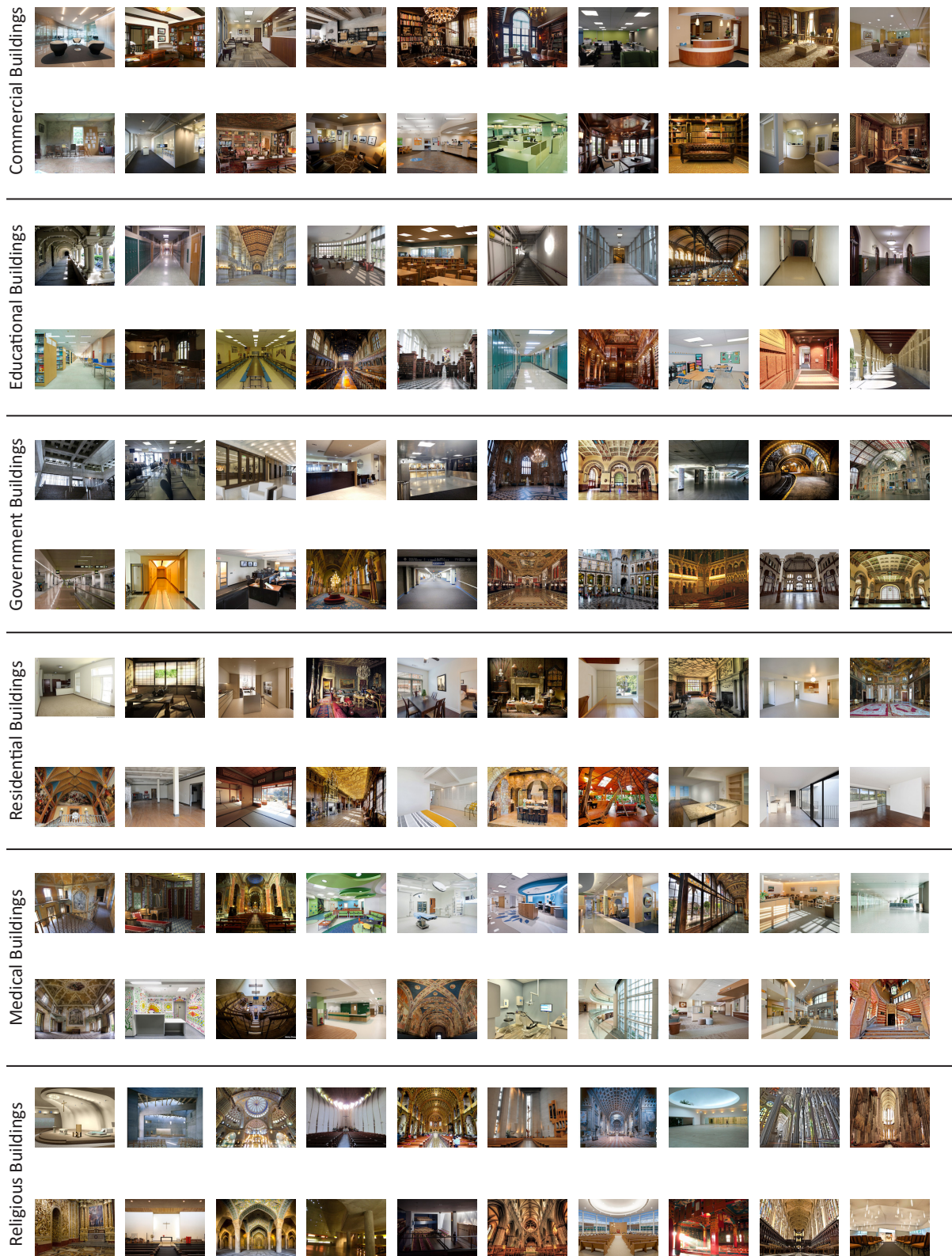


Figure B1: Experimental stimuli (Interiors)

## APPENDIX B

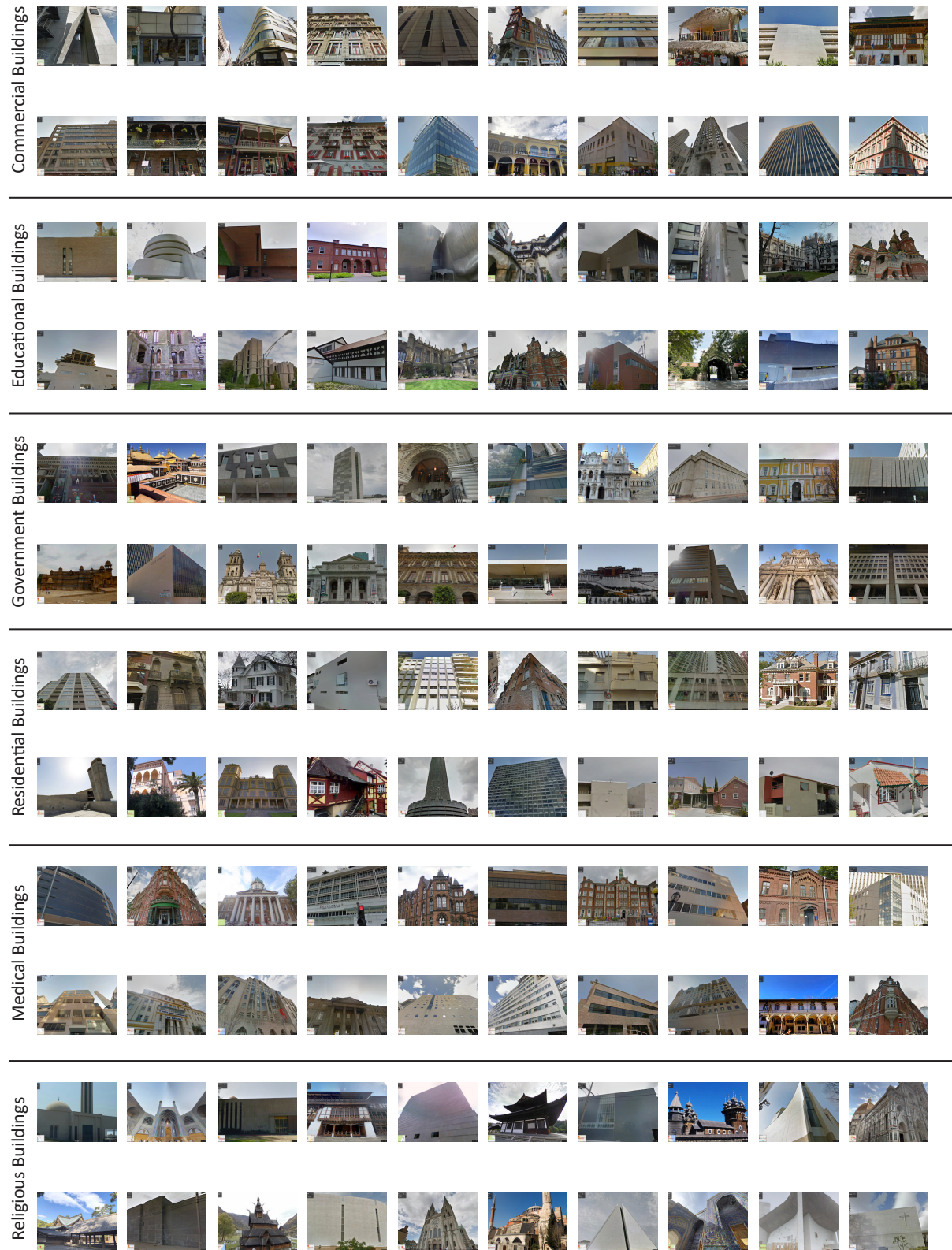


Figure B2: Experimental stimuli (Exteriors)

## Building Function Analyses

**Table B1: Deviation Contrasts for ANOVA of Naturalness vs. Building Function (Interiors)**

Comparison	Estimate	SE	t value	P value
Educational - Mean	-0.022	0.18	-0.12	0.904
Government - Mean	0.174	0.18	0.968	0.335
Medical - Mean	0.32	0.18	1.785	0.077
Religious - Mean	-0.206	0.18	-1.146	0.254
Residential - Mean	-0.194	0.18	-1.082	0.281

$$\eta_p^2 = 0.047, F(5, 114) = 1.31, p = 0.35$$

**Table B2: Deviation Contrasts for ANOVA of Preference vs. Building Function (Interiors)**

Comparison	Estimate	SE	t value	P value
Educational - Mean	0.371	0.213	1.745	0.084
Government - Mean	0.138	0.213	0.647	0.519
Medical - Mean	0.048	0.213	0.225	0.822
Religious - Mean	-0.29	0.213	-1.361	0.176
Residential - Mean	-0.278	0.213	-1.304	0.195

$$\eta_p^2 = 0.049, F(5, 114) = 1.18, p = 0.32$$

**Table B3: Deviation Contrasts for ANOVA of Naturalness vs. Building Function (Exteriors)**

Comparison	Estimate	SE	t value	P value
Educational - Mean	-0.173	0.165	-1.051	0.296
Government - Mean	0.104	0.165	0.63	0.53
Medical - Mean	0.193	0.165	1.173	0.243
Religious - Mean	-0.191	0.165	-1.158	0.249
Residential - Mean	0.002	0.165	0.011	0.992

$$\eta^2 = 0.031, F(5, 114) = 0.73, p = 0.60$$

**Table B4: Deviation Contrasts for ANOVA of Preference vs. Building Function (Exteriors)**

Comparison	Estimate	SE	t value	P value
Educational - Mean	-0.094	0.219	-0.43	0.668
Government - Mean	-0.29	0.219	-1.322	0.189
Medical - Mean	0.167	0.219	0.763	0.447
Religious - Mean	-0.351	0.219	-1.598	0.113
Residential - Mean	0.43	0.219	1.96	0.052

$$\eta^2 = 0.064, F(5, 114) = 1.55, p = 0.18$$

# **Appendix C: Pilot study of natural structure and wellbeing in Cambridge residential halls**

## **Introduction**

The following is a brief overview of the methods and findings of a pilot study conducted in April 2015, as a preliminary attempt to test the two early hypotheses of the PhD:

- **Hypothesis 1:** The perceived phenomenon of “life,” where present, is a highly agreed-upon quality that tends to pervade the whole structure of any given building.
- **Hypothesis 2:** Occupants of residential buildings with higher degrees of “life” tend to experience comparatively higher “symptoms” of well-being while at home.

These hypotheses were tested in a natural experiment measuring environmental quality and student well-being in two residential dormitories predicted to have very different degrees of life.

## **Methods**

### **Building selection**

Two buildings were selected for comparison in this study in order to maximize differences in environmental quality, so that effects on wellbeing (if present) would be large enough to measure, and in order to minimize population differences, so that the independent variable (environmental quality) would be isolated as much as possible.

The buildings were chosen based on the following criteria:

- 1) The two buildings compared were geographically close to one another and part of the same academic institution.
- 2) The two buildings compared differed significantly in their structural geometry, with the expectation that one would be evaluated as having a higher degree of “life” than the other.
- 3) The two populations of building occupants were demographically similar to each other.
- 4) The two populations of building occupants were randomly assigned to live in each building.
- 5) The two populations of building occupants lived in their respective buildings for similar periods of time.
- 6) The two populations of building occupants were willing to take part in the proposed research.
- 7) It was financially and practically feasible for the author to access the buildings and carry out the research.



## APPENDIX C

The two buildings selected for comparison, Margaret Wileman House and Fenner's Dormitory at Hughes Hall, are located within 100 yards of each other at the same Cambridge University college, Hughes Hall. These two buildings are of comparable size and occupant density but exhibit very different structural properties. Margaret Wileman House was predicted to have a high degree of natural structure or "life," whereas Fenner's was predicted to have a low degree of architectural "life."



**Figure C1: Margaret Wileman House (Left); Fenner's Building (Right)**

All survey participants had lived in the respective buildings from September – May, 2015 and were graduate students at the University of Cambridge. Most, but not all, participants were first-year students who had had been assigned to live in the buildings by the college housing coordinator. Survey participants were demographically mixed (all between ages 21 and 30) and studied a range of subjects, although there was a high concentration of Master of Education students living in Margaret Wileman House as well as a high concentration of MBA students in Fenner's Hall. Since residents of both buildings all lived there for the same time period, had access to the same college, university, and town facilities, and had been assigned to live in the buildings, this study could be considered a longitudinal natural experiment. All surveys were conducted during the same week, 20-24 April, by the author knocking on residents' doors between 6-10pm each evening.

### **Measuring environmental quality**

Environmental quality was measured using modified versions of Christopher Alexander's "degree of life" tests (Alexander, 2002). Residents of both buildings who participated in the well-being surveys also filled out "degree of life" surveys. Every participants was shown nine pairs of photographs, each comparing a pair of equivalent spaces or architectural features in Margaret Wileman House and Fenner's Building. For each pair of comparative photographs,

## APPENDIX C

the participant was asked to respond to one of the following two questions, depending on which of two questionnaires they were randomly given.

- Which building, of the two, feels more alive?
- Which building, of the two, feels more natural?

Photographic comparisons of other buildings were also mixed in with those of interest. Recognizing that participants' intuitive perceptions of the photographs might be biased by their personal experiences in these two buildings, a second set of "degree of life" surveys was distributed to two classes of 8<sup>th</sup> grade (12-14 year old) students at Trevor Day School in New York City. These students were given the same photographs to judge as the students in England and they were not informed of the locations of the buildings or the purpose of the survey.

### **Measuring subjective well-being**

Well-being was measured by self-report survey. 19 participants from each building filled out three surveys each:

- The Subjective Vitality Survey (Ryan et al., 2010)
- The Warwick-Edinburgh Mental Well-Being Scale (Tennant et al., 2007)
- The Resident Social Survey (Coburn, 2013)

Two-sample T-tests were then performed for each environmental metric to compare the sample means for the two residential populations.

## **Results**

Results from the degree of life surveys are displayed in Table C. A high percentage of participants judged that photographs of the spaces in the Margaret Wileman House felt more "alive" (76%) and "natural" (81%) than photographs of equivalent spaces in Fenner's Building. Respondents felt this way about nearly all of the spaces considered. Margaret Wileman photographs prevailed in the head-to-head comparisons by a score of 31-2, with one tie. The data suggests that these environmental qualities, as perceived by respondents, did not vary greatly from one space to the next within each building, but rather seemed to pervade the whole structure.

Equally intriguing is the level of consistency between the New York and Cambridge surveys. Some well-being researchers have theorized that perception of environmental quality differs

## APPENDIX C

significantly between groups of people and especially across cultures, and that individuals' lived experiences in different environments also sway their opinions so as to make them fairly subjective and inconsistent (Cooper & Burton, 2014; Porteous, 1971). In this study, however, thirteen year-old respondents in New York City who had no firsthand experience with these buildings expressed similar perceptions of how "alive" and "natural" they felt as older, mainly European students who had lived in the buildings for a year. Both groups of respondents, interestingly, reversed their usual choice of Margaret Wileman in comparison #2 of the common spaces, but collectively agreed on all of the other comparisons. Although there were certainly variations between the two populations of respondents, these results suggest the possibility of an underlying thread of agreement between people of different backgrounds and different life experiences that may have to do with the fundamental ordered complexity of the environments. These consistencies of spatial judgment supported Hypothesis 1 and motivated the author to pursue the experiments presented in Chapter 5 of the dissertation.

**Table C1: Results of degree of life surveys of Hughes Hall and Trevor Day School students**

Which feels more alive? (Hughes)	Margaret Wileman	Fenner's
Photo #1 (Front Façade)	75%	25%
Photo #2 (Common Room)	50%	50%
Photo #3 (Hallway)	94%	6%
Photo #4 (Doors)	80%	20%
Photo #5 (Main Staircase)	100%	0%
Photo #6 (Windows)	75%	25%
Photo #7 (Entrance Doors)	81%	19%
Photo #8 (Toilet)	88%	13%
Photo #9 (Back Façade)	63%	38%
<b>TOTAL (# WINS)</b>	<b>8</b>	<b>0</b>
<b>TOTAL (%)</b>	<b>78%</b>	<b>22%</b>
Which feels more natural? (Hughes)	Margaret Wileman	Fenner's
Photo #1 (Front Façade)	100%	0%
Photo #2 (Common Room)	59%	41%
Photo #3 (Hallway)	94%	6%
Photo #4 (Doors)	88%	12%
Photo #5 (Main Staircase)	94%	6%
Photo #6 (Windows)	94%	6%
Photo #7 (Entrance Doors)	94%	6%
Photo #8 (Toilet)	94%	6%
Photo #9 (Back Façade)	88%	12%
<b>TOTAL (# WINS)</b>	<b>9</b>	<b>0</b>
<b>TOTAL (% VOTES)</b>	<b>90%</b>	<b>10%</b>

Which feels more alive? (Trevor)	Margaret Wileman	Fenner's
Photo #1 (Front Façade)	63%	38%
Photo #2 (Common Room)	25%	75%
Photo #3 (Hallway)	81%	19%
Photo #4 (Doors)	81%	19%
Photo #5 (Main Staircase)	94%	6%
Photo #6 (Windows)	94%	6%
Photo #7 (Entrance Doors)	69%	31%
Photo #8 (Toilet)	81%	19%
Photo #9 (Back Façade)	n/a	n/a
<b>TOTAL (# WINS)</b>	<b>7</b>	<b>1</b>
<b>TOTAL (%)</b>	<b>76%</b>	<b>24%</b>
Which feels more natural? (Trevor)	Margaret Wileman	Fenner's
Photo #1 (Front Façade)	80%	20%
Photo #2 (Common Room)	27%	73%
Photo #3 (Hallway)	80%	20%
Photo #4 (Doors)	93%	7%
Photo #5 (Main Staircase)	67%	33%
Photo #6 (Windows)	80%	20%
Photo #7 (Entrance Doors)	67%	33%
Photo #8 (Toilet)	73%	27%
Photo #9 (Back Façade)	n/a	n/a
<b>TOTAL (# WINS)</b>	<b>7</b>	<b>1</b>
<b>TOTAL (% VOTES)</b>	<b>71%</b>	<b>29%</b>

The findings of the three occupant well-being surveys are shown in Table C. 2-sample T-tests revealed statistically higher sample means in Margaret Wileman House for nine of the 17 well-being measures taken, including subjective vitality, one of the most robust single

## APPENDIX C

measures of well-being (Ryan & Frederick, 1997). Residents of the Margaret Wileman House also scored significantly higher on three questions of the WEMWBS and reported significantly more pro-social behaviour for six of the seven measures of the Resident Social Survey. This data supports Hypothesis 2 and calls for further exploration of the relationship between natural structure and well-being in future experiments.

**Table C2: Results of subjective vitality survey, WEMWBS survey, and resident social survey**

Well-Being Measure	Mean (Margaret Wileman)	Mean (Fenner's)	Pooled Variance	t stat (18)	P(T<=t) one-tail
<b>Subjective Vitality</b>	<b>4.40</b>	3.76	1.23	-1.78	<b>0.04</b>
<b>Cheerfulness</b>	<b>3.74</b>	3.37	0.39	-1.81	<b>0.04</b>
<b>Optimism</b>	<b>3.79</b>	3.42	0.44	-1.71	<b>0.05</b>
<b>Relaxation</b>	<b>3.68</b>	3.37	0.63	-1.23	0.11
<b>Sense of Purpose</b>	3.16	<b>3.37</b>	0.47	0.95	0.18
<b>Positive Relationships</b>	<b>3.47</b>	2.95	0.88	-1.73	<b>0.05</b>
<b>Environmental Mastery</b>	<b>3.74</b>	3.63	0.39	-0.52	0.3
<b>Competence</b>	3.58	<b>3.63</b>	0.53	0.22	0.41
<b>Self-Esteem</b>	<b>3.68</b>	3.58	0.41	-0.51	0.31
<b>Spatial Autonomy (reverse)</b>	<b>2.42</b>	2.53	0.98	0.33	0.37
<b># Path Crossings / Week</b>	<b>17.2</b>	5.1	183.74	-2.3	<b>0.01</b>
<b># Room Visits / Week</b>	<b>6.13</b>	0.47	29.47	-2.99	<b>0.003</b>
<b># Initials Known</b>	<b>12.32</b>	3.94	29.27	-4.64	<b>&lt;0.001</b>
<b># Phone Number Known</b>	<b>6.47</b>	3.94	24.97	-1.48	0.07
<b># Academic Exchanges</b>	<b>4.18</b>	1.28	10.08	-2.62	<b>0.01</b>
<b># Instrumental Exchanges</b>	<b>5.53</b>	2.21	11.22	-2.93	<b>0.003</b>
<b># Personal Conversations</b>	<b>19.47</b>	6.21	401.82	-1.81	<b>0.04</b>